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# TRENDS IN PETROLEUM GEOLOGY.[1]

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ABSTRACT.

One of the peculiarities of the oil industry, in which it differs from many of the other industries using the minerals of the earth, is that its supplies of crude oil must be replenished continually by new discoveries. It is in the field of oil discovery that the petroleum geologist finds his chief work.

The use of the microscope, with the consequent increase in detailed and accurate stratigraphic data has been proved one of the most important tools of petroleum geology. Not only does it give a better understanding of underground stratigraphy, but it also has stimulated an awareness of the importance of geologic history in the discovery process. The present trend is strongly in the direction of the application of this sort of data to the problems of stratigraphy and sedimentation.

There is a growing trend of petroleum geologists into executive and managerial positions within the industry and into the oil business as independent operators. Probably as a result of this broadening viewpoint, there is developing a greater interest in the college curricula of geological colleges. In many ways, the petroleum geologist is becoming an "oil man," which, after all, is proof of his place in the industry.

THE oil industry, like other great American industries, has made effective use of the most advanced thinking in many scientific fields. This is particularly true of its applications of physics, chemistry, engineering and geology. As a matter of fact, the steep upward curve of the expansion of the industry during the past quarter century merely reflects the increasing use of the sciences in the discovery, drilling, producing, refining and transporting operations. And, of the sciences that have been employed,

[1] Read at the Fiftieth Anniversary Celebration of the University of Chicago, September 1941.

none has had a more spectacular rise in usefulness than geology and its close relative, geophysics.

The oil industry differs from most other industries that use the mineral deposits of the earth, in one important respect, however, in that its supplies must continue to be replaced by new discoveries. Whereas, in the field of coal, the supply for generations to come has been discovered, is proved, and is known, the situation in oil is quite the reverse. The oil that our children will use is not yet discovered—and being undiscovered, its location, quantity, and nature are not known. This situation is largely the result of the economic cycle of supply and demand—as the supply increases, the price goes down, and the incentive to discover new supplies wanes. Equilibrium seems to be reached, on the average, when the known reserves are kept at approximately 15 times the current yearly demand—a demand that completely consumes the supply and leaves no residue with which to cushion an emergency. The gas tank of this modern engine of progress must, therefore, be continually replenished and as long as this condition prevails there will be a need for methods and techniques of discovery.

There is now an estimated known reserve of 18 to 20 billion barrels of oil underground—oil which has been discovered, is blocked out, and is available for use. This quantity is adequate only if new discoveries can be made to replace it as it is produced and consumed. The past ability of the industry to maintain discovery has been essential to its growth, and if it should fail to find new supplies, it would quickly relapse into a stifling routine operation and gradually stagnate.

The primary work of the petroleum geologist is in the field of oil discovery. His work is, therefore, fundamental and of vital importance, not only to the economy of the industry, but of the nation as well, for oil has certainly become one of the necessities of well being for this age. He does many other kinds of work within the industry, particularly in the scouting, leasing, and production departments, but failing of discovery, they would all be of little value, for everything he does is subordinate to his function in the maintenance of supplies of crude oil.

Probably as good a measure as any of the role of science in the discovery process is to be found in the most recent of the annual surveys made by Lahee[2] of the basis upon which wildcat well locations were made in 1940. During this year he finds that of the 3038 wildcat wells drilled, 2051, or approximately two-thirds, were drilled because of geological and geophysical reasons, and of the remaining one-third, most were drilled for various non-technical reasons and part for unknown reasons. Moreover, he finds that of the wells drilled on technical advice, 15.6 per cent were producers as against only 4.2 per cent successful in the case of wells drilled for non-technical reasons. It was, therefore, nearly four times as advantageous to use technical reasons for making wildcat locations as to use non-technical reasons.

One of the curious situations in petroleum geology is that in spite of our theories, and all of the workers who have given thought to the problem, little is known of the origin of oil, how it migrates, or how it accumulates. About all that is known is that it is now found in traps of various kinds, and as a consequence, almost the entire geological effort toward discovery consists in the search for such traps. The most obvious trap is an up-fold or deformation of the earth's strata which will keep the oil within the affected area. In the idiom of the profession, these are called "structures" and a pool which produces from such an anomaly is called a "structural pool."

Less obvious and much more difficult to find are those traps that result from a variation in the porosity or in the stratigraphy of the reservoir rock. Pools producing from such situations are called "stratigraphic" pools. Random drilling has been particularly adapted to the discovery of "stratigraphic" pools, for in them we find no guiding surface or shallow indications. Most of the oil fields of the great producing areas of Ohio, Pennsylvania, West Virginia, and Indiana, together with those within the Pennsylvanian sediments of the Mid-Continent region, are of the stratigraphic type and were discovered largely by the early "wild-

[2] Lahee, F. H.: Wildcat drilling in 1940. A. A. P. G. Bull. 25: 997–1003, June, 1941.

catter" who followed whatever hunch seemed best to fit the occasion. Such drilling was totally unscientific but because there were so many shallow stratigraphic pools to discover, it was effective, and many fortunes were built and large quantities of oil were found.

The approach of the petroleum geologist to the problem of finding traps that might contain oil has been chiefly through his ability to locate favorable structural areas, either by surface or subsurface geology, or by geophysical methods. However, as he is forced to search deeper and deeper for his data, and as it is becoming more difficult to find untested "structures," the expense keeps mounting, and he is gradually turning his attention to the possibilities of finding stratigraphic type pools. The ammunition he brings into use for such work includes the microscope, the electric log, paleo-geology, paleo-geography, imagination, and speculative reasoning based on sound fundamental geological concepts. The tide of exploratory thinking is running strongly in this direction at present, and the possibilities for success are almost unbelievably great.

Probably the most important development of the past decade, and an approach that is still in its infancy, is the continually widening use being made of well cuttings, cores, electrical logs, and all sorts of detailed stratigraphic data. It calls for a technique which, in part, was forced upon the petroleum geologist when drilling methods changed from the use of cable tools to the use of rotary equipment. At that time the driller was unable to make a satisfactory log of the well he was drilling and the geologist was called on to do it for him. This he did through the use of the microscope, and the resulting additions to our knowledge of the stratigraphy, sedimentation, geologic history, paleontology, and structure in much of the sedimentary area of the United States is so vast as to make almost all previous data obsolete and insignificant.

Not only do detailed stratigraphic and sedimentation studies furnish the background for modern subsurface work, but they are also the basis for any scientific search for pools of the stratigraphic

type. The operator attempting to find such a pool with a minimum of drilling is indeed sorely in need of geologic assistance. In a way it is like the children's game of Hide the Button, the difference being that the operator now expects the skilled sedimentationist and micro-paleontologist to tell him when he is getting "hot" or when he is getting "cold."

In discussing this question of the trend of petroleum geology with one of the geologists of the Gulf Coast region, I could not help but agree with him when he stated, that in his opinion, the trend could be expressed in one word and that word was "downward." He went on to explain that he did not mean that we were going into a decline, but that the thought and the effort of the petroleum geologist was more and more being concentrated below the surface and in the realms of subsurface sedimentation, subsurface stratigraphy, and subsurface paleontology. This entire subsurface development stems directly from the place microscopic methods have taken as a technique of petroleum geology. A person working with subsurface geology began with the terms of the well drillers—"hard rock," "soft rock," "mud," "slate," and the like. Gradually he was able to change those to terms with a more geological sound—limestone, sandstone, and shale, and, as a further refinement, added such general textural and qualifying terms as crystalline, dense, lithographic, porous, sandy, dolomitic, calcareous and argillaceous. Now, we find him beginning to examine microscopically the individual mineral grains and to reduce their primary characteristics to the simplest possible terms; we find him concerned deeply with slight changes in facies; and we find he is beginning to look into the possibilities of distinguishing the variations of single minerals as a guide to the sedimentary environments of deposition. Some think it is deplorable, but it is nevertheless true in petroleum geology, that the microscope has pretty well supplanted the plane table and stadia rod as the leading method of obtaining geologic data.

Geophysical methods have become so well established in the oil-finding technique as to have long since passed beyond the trend stage. Moreover, it is not the purpose of this discussion to go

into other than the strictly geological aspects of petroleum exploration, leaving to others the telling of the brilliant contribution geophysics is making to the oil industry.

The chief function of geophysics in petroleum exploration, is to obtain structural data in advance of drilling. Geophysical data, in order to be effective, require geological interpretation and so far this has been successful only in the search for structural accumulations. The time will certainly come, however, when the geologist will be able to interpret geophysical data in terms of sedimentation and stratigraphy and then the entire field of stratigraphic type oil pools will be opened to geophysical methods. Since geophysical data are all below the surface of the ground, when they are added to the steady stream of subsurface well data, they further tend to push our thinking deeper and deeper. Even now the commercially accurate mapping of geologic conditions five, ten, or even more thousands of feet underground is a daily routine in many areas.

As the exploratory effort becomes deeper, it becomes more complex, and it also increases rapidly in cost. There is a tendency, therefore, in some quarters to go back to a reinterpretation of surface and subsurface information for the reason that many of the discoveries of the past, which have been attributed altogether to geophysical methods, would or could have been made by ordinary geological techniques at a much lesser cost.

Obviously, there is much yet to be learned from surface mapping. One important factor is the availability of aerial photographs in nearly all regions, which force into the discard the methods and standards of accuracy that prevailed even a decade ago. Another factor, which has been the cause of many failures of interpretation, is the almost universal presence of unconformities. When a surface fold is projected through two or three unconformities, one or more of which is associated with diverging thickness of sediments, the expression of the fold at the surface has but a faint resemblance to what is found at five or ten thousand feet below it. A third factor that applies to surface geology is that most of the early work was solely concerned with

a search for anticlines and other types of favorable deformation. Many regions are therefore being re-worked and the detailed stratigraphic information, which was neglected in the first surveys, is now being added. In my own experience, I well know that the year I spent in mapping "structures" in the San Juan Basin of New Mexico could be repeated to better advantage by mapping the stratigraphy and its relation to possible oil accumulation.

This brings us to another trend which is apparent, and that is a growing awareness of the importance of geologic history in the search for new oil fields and new oil provinces. It is expressed in the deep interest of geologists in unconformities, overlaps, wedge belts of porosity, paleogeology, lateral and vertical gradation of porosity and permeability, facies changes, and in all of the varied phenomena of sedimentation. We may think of the rocks between each regional unconformity as being in layers of geology—each layer having its own peculiarities of sedimentation, structure, stratigraphy, and value as a potential oil producing unit. In some regions, notably West Texas and Northern Louisiana, as many as four such layers are being explored and each found productive. Many other developed areas have shown two or three such separate and distinct layers of geology, and we may, therefore, conclude that much of the unexplored territory of the United States, undeveloped because it was thought to be uninteresting and monotonously uniform from a shallow structural viewpoint, now takes on value, because it likewise may be underlain by two or more additional layers of geology. Thus, the first clues to the possibilities of a new region may not appear until one starts exploring five, six, or eight thousand feet below the surface, and thinking through one, two, or three regional unconformities. The almost infinite number of combinations of structure and stratigraphy that have in the past been found to produce oil, if projected into the future and considered as possibilities of accumulation in each or any of these unexplored layers of geology, reveals a correspondingly large undiscovered future oil reserve and the enormous geologic effort necessary to find it.

Most petroleum geologists began working in two dimensions—length and breadth at the surface. Later, as more wells were drilled, a third dimension, depth, was added. They now find themselves thinking and applying a fourth dimension to their work—geologic time—and as with the other dimensions, its addition to their kit gives the horizon yet another push outward.

The only really new approach to the problem of oil discovery that has developed in many years is the recent use of earth- or geo-chemistry. Its approach differs from geological and geophysical systems because it is a direct method, dependent only on the presence of oil regardless of the kind of trap, whereas the older methods are all concerned solely with the search for favorable structure, in which it is hoped oil may be found.

Many claims have been made for geo-chemical methods and if they were all realized it would be but a short time until all of the oil fields in the world were found. However, there are many geological objections to its philosophy, and so far there have been very few or no oil fields found as the sole result of its application. Until it proves itself to be successful, it will probably continue to be regarded with a considerable amount of restraint as an instrument of discovery. We should not forget, however, that much highly intelligent experimentation and research is going on continually in this field, and that we may well see the day when it, or some modification of the present method, is a generally accepted tool of oil exploration.

A development in petroleum geology, which I believe is significant, is of a different nature since it deals with the geologist rather than with his thinking. It is the trend in the oil industry to place geologically trained and experienced men in executive and managerial positions. It is coming on at an ever accelerating pace and in nearly every month that passes we hear reports of promotions and changes in which geologists are advanced into positions of authority outside their normal field of activity. As Pratt [3] has so well put it, the geologist now "per-

[3] Pratt, Wallace: Geology in the petroleum industry. A. A. P. G. Bull. 24: 1209–1213, July, 1940.

meates the industry," and he has come in " like a metasomatic phenomenon in ore deposits in which the invading solution completely changes the internal character without changing the outward appearance."

This trend has far reaching consequences. Although in the early days the petroleum geologist was practically limited in his application of geology to discovery by his ability to make the non-technical executive understand what he was trying to do, now he finds a more tolerant and understanding attitude in the executive departments, which leaves him more freedom to concentrate on his geology without the necessity of promoting it or selling it to someone with no conception of its philosophy or method. Nothing cools the enthusiasm of a scientist as quickly as an unsympathetic superior, and this handicap, which has prevailed in too many instances, is rapidly being lifted to the ultimate good of both the industry and the science.

Not only is the geologist going into executive positions within the larger units of the industry, but he is also going into the oil business for himself in continually increasing numbers. He may call himself a consulting geologist, but more often than not he is buying and selling oil and gas leases, drilling wildcat wells, and has oil or gas production of his own. The study of geology and its method of thinking is good training for anyone entering the oil industry in a similar manner to the study of law, which has long been considered a good background for entry into business in general.

DeGolyer [4] has pointed out another significant change in the work of the petroleum geologist in that he is becoming more and more a co-ordinator of a variety of geologic data, all of which are obtained by experts and turned over to him for interpretation. This contrasts strongly with the older methods, where the geologist went into the field himself to get the data, and returning to his office, made his interpretation. Then, one geologist did all of the geological work incident to the drilling of a wildcat well;

[4] DeGolyer, E.: Future position of petroleum geology in the oil industry. A. A. P. G. Bull. 24: 1389–1399, August, 1940.

now there may be a dozen or more specialists, each securing data of various kinds, which are put together by the office geologist into a coherent and related whole. Thus, today the exploration problem is complex and the high costs prior to drilling a wildcat well may even approach the cost of the well itself. If one is to succeed at this kind of interpretive geology, the need for the best possible training is obvious.

One of the healthy signs in petroleum geology, therefore, is the interest that is being shown in the college curricula of geology departments. This was aptly put by a petroleum geologist the other day when he said, in discussing one of his college professors, "I worship the very ground he walks on, but he is teaching ten years behind the times. Something ought to be done about it."

Well, something is being done about it. After studying all of the college catalogues of geology curricula and after sending out many questionnaires, a committee of interested geologists appointed by Henry Ley, President of the American Association of Petroleum Geologists, have made a preliminary report.[5] In it they concluded, in part, that more attention in college training should be given to English composition, mathematics, chemistry, physics, descriptive geometry, logic or the ability to reason accurately, foreign language, sedimentation, geophysics, and field work. Biology might well be added to such a list also. Apparently the teaching of the strictly geological subjects meets their approval but they feel there should be more training in the fundamentals of science in what might be called "background" studies. They also favored more problem courses and fewer memory studies in the preparation for a career as a petroleum geologist. In order to do all this and still have time to do the essential work in geology, they believe the standard course of study should be for a term of five years, instead of four, as at present.

I rather think this interest in college curricula is traceable to the general broadening of the viewpoint of the petroleum geologist. As he takes a more active and responsible part in the oil industry;

[5] Report of Special Committee on College Curricula, F. H. Lahee, Chairman A. A. P. G. Bull. 25: 969–972, May, 1941.

as he goes into the oil business for himself; and as his strictly geological duties require greater imagination, more sound reasoning, and a broader basic understanding of the interrelation of the various sciences, so he comes to realize his own shortcomings and the need for better preparatory training for those now in the colleges. In effect, this means that the specialized field of petroleum geology is coming of age and is commencing to think about building its own standards of training and achievement.

Thus we see that geology and geologists are exercising a constantly expanding influence on the whole business of finding and producing oil and gas. There is no sign of a slowing down of this trend of usefulness, but, on the contrary, it is accelerating steadily, year by year. The petroleum geologist is becoming an " oil man " in every sense of the word, which, after all, is the best proof that he is keeping pace with the other applied sciences in the forward moving front of scientific progress.

TULSA, OKLAHOMA,
*Nov. 4, 1941.*

# ROLE OF FUNDAMENTAL GEOLOGIC PRINCIPLES IN THE OPENING OF THE ILLINOIS BASIN.[1]

ALFRED H. BELL.

ABSTRACT.

The opening of the Illinois basin to oil production in 1937 was the beginning of a large-scale development that restored Illinois to the position of a major oil producing state after the lapse of a quarter-century. The delay in the opening of the Illinois basin was the result of several factors, the most important of which was perhaps the theory that oil had migrated outward from the central parts of large structural basins and that consequently the central parts were barren of oil and not worthy of prospecting.

This paper discusses first the sequence of events leading up to the discovery of oil in the Illinois basin, with special emphasis on the influence of geologic theory, second the application in the area of the new techniques of exploration and development including geophysical methods, rotary drilling, and electric logging. The use of the reflection seismograph method proved highly successful.

## INTRODUCTION.

THE discovery of oil in the Illinois basin in 1937 was the beginning of a rapidly expanding new development of oil production which now, nearly five years later, is still in progress. It restored Illinois to the position of a major oil-producing state after a lapse of a quarter-century. The purpose of this paper is to discuss the circumstances which led to the development of the Illinois basin oil fields with special regard to the influence of geological theory. In view of the magnitude of these oil deposits, their proximity to old producing fields, and their relatively shallow depth as compared with many of the new fields in other states, it is natural to inquire why they remained so long undeveloped.

[1] Read at the Fiftieth Anniversary Celebration of the University of Chicago, September, 1941.

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ILLINOIS BASIN.

The term, Illinois basin,[2] is applied in this paper to the central deepest portion of the Eastern Interior basin (Fig. 1). It includes approximately 8000 square miles between the Centralia-

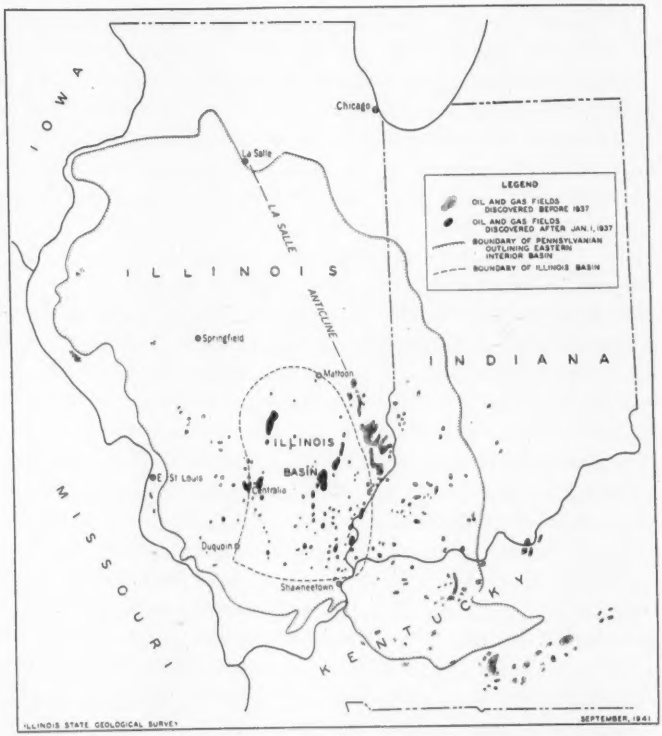



FIG. 1. Map of Eastern Interior basin and Illinois basin showing oil and gas fields.

[2] The term "Illinois basin" has sometimes been used as an alternative for Eastern Interior basin. However, several earlier writers, including R. S. Blatchley (I. G. S. Bull. 16, 1909, pp. 63, 97, 110, 129) and L. A. Mylius (I. G. S. Bull. 54, p. 28, Pl. I) confined the term "Illinois basin" to an area west of the LaSalle anticline and therefore did not use it as a synonym for "Eastern Interior basin."

DuQuoin monocline on the west and the LaSalle anticline on the east (70 miles) and approximately from the latitude of Mattoon on the north to that of Shawneetown on the south (125 miles).

## HISTORICAL BACKGROUND.

Oil production of minor importance was obtained in western Illinois near Litchfield about 1886, and production in this field continued until 1903. In 1904 a gas well was drilled in what is now the Westfield pool in Clark County. This was followed by an oil well nearby in 1905 opening the Southeastern Illinois oil field, one of the nation's major fields. In 36 years this field has produced 430 million barrels of oil or 61 per cent of the State's total production to date. Prior to the opening of the Illinois basin in 1937, however, the Southeastern Illinois field had yielded 98 per cent of the State's total. Therefore, up to 1937, the oil history of Illinois is largely the history of one major field. The peak of production for that period came in 1908 when Illinois produced 33.7 million barrels and ranked third in the nation. From 1910 to 1936 the State's production declined rather steadily to a level of less than 4½ million barrels annually.

Beginning about 1910 some important oil discoveries were made in Oklahoma, and these proved to be sufficiently attractive to draw away from Illinois in the next few years many of the oil men most active in "wildcatting." Some good but small oil fields had been discovered in western Illinois—for example, Sandoval in 1908 and Carlyle in 1911—but nothing to compare with the Southeastern Illinois field. One thing that encouraged prospecting in this marginal area to the west of the Illinois basin was the large amount of information on subsurface structure provided by coal data in mines and test borings. However, in the Illinois basin itself, few data on bedrock structure were available because there was very little coal mining or prospecting, and because the bedrock is hidden by glacial drift or alluvium throughout large areas.

Because structural data on the Illinois basin were meager, there was a tendency for geologists to assume that it was a simple flat-bottomed geosyncline, uninterrupted by folds or other structures

that might serve as oil traps. Furthermore, test wells drilled west of the west edge of the Southeastern Illinois oil field found the oil sands structurally lower and saturated by salt water. Hence, by extrapolation, the conclusion was reached that the sands contained nothing but salt water across the basin.

Another consideration that pointed to the same conclusion was the theory of hydraulic accumulation and long-distance migration of oil. According to this theory, water and oil migrate outward from the central parts of large basins, and the oil accumulates in underground traps in the marginal areas, leaving the central parts barren of oil.

Strangely enough there was already a perfectly good demonstration of the occurrence of commercial deposits of oil and gas in the central parts of geosynclines in the fields of western Pennsylvania, West Virginia, eastern Ohio and Kentucky, all within the Appalachian geosyncline. The failure to apply this lesson earlier in the Michigan and Illinois basins may have been due to the idea that the Appalachian geosyncline is a different type of structure, being long and narrow and situated adjacent to the belt of intense folding of the Appalachian Mountains. Another difference appeared in the fact that some of the Appalachian basin fields, for example the Copley and Cabin Creek fields in West Virginia, have no water in the oil sands. The Pure Oil Company, however, entered upon a program of extensive pioneer exploration work in the Michigan basin, and it took the jolt of that company's discovery of oil at Mt. Pleasant in the center of the Michigan basin in 1928 to cause geologists elsewhere to consider seriously the oil possibilities of the Illinois basin.

Recognition by geologists of favorable prospects for oil production in the Illinois basin was only the first step toward actual development. It was then necessary to formulate plans for exploring this extensive territory. Recommendations for such planning are contained in a paper presented by the writer [3] before the Illinois Academy of Science in May 1930.

[3] Bell, A. H.: The relation of geology to the development of the petroleum industry of Illinois. Illinois Acad. Sci. Trans. 23, No. 3: 367–370, 1931.

FIG. 2. Map classifying oil and gas possibilities in Illinois prepared in 1930, showing location of oil and gas fields as of September 1941.

INDEX TO POOL NUMBERS.

*Name of Pool—County*

1 Colmar-Plymouth—McDonough, Hancock
2 Pittsfield (gas, abd. 1930)—Pike
3 Jacksonville (gas, abd. 1937)—Morgan
4 Carlinville (abd. 1925)—Macoupin
5 Spanish Needle Creek (gas, abd. 1931)—Macoupin
6 Gillespie-Wyen—Macoupin
7 Gillespie-Benld (gas, abd. 1935)—Macoupin
8 Staunton (gas, abd. 1919)—Macoupin
9 Collinsville (abd. 1921)—Madison
10 Dupo—St. Clair
11 Waterloo—Monroe
12 Waggoner—Montgomery
13 Raymond—Montgomery
14 Litchfield (abd. 1904)—Montgomery
15 Sorento—Bond
16 Ayers (gas)—Bond
17 Woburn—Bond
18 Greenville (gas, abd. 1923)—Bond
19 Frogtown (abd. 1933)—Clinton
20 Carlyle—Clinton
21 Bartelso—Clinton
22 Posey—Clinton
23 Hoffman—Clinton
24 Centralia—Clinton, Marion
25 West Centralia—Clinton
26 Irvington—Washington
27 McKinley—Washington
28 Cordes—Washington
29 Dubois—Washington
30 Sparta (gas, abd. 1900)—Randolph
31 Ava-Campbell Hill (gas, abd. 1934)—Jackson
32 Elkville—Jackson
33 Lakewood—Shelby
34 Stewardson—Shelby
35 Louden—Fayette, Effingham
36 St. James—Fayette, Effingham
37 Patoka—Marion
38 Patoka (East)—Marion
39 Fairman—Marion, Clinton
40 Sandoval—Marion
41 Tonti—Marion
42 Junction City—Marion
43 Salem—Marion
44 Langewisch-Kuester—Marion
45 Brown—Marion
46 Wamac—Marion, Clinton, Washington
47 Cravat—Jefferson
48 Dix—Jefferson
49 Roaches—Jefferson
50 Woodlawn—Jefferson
51 Marcoe—Jefferson
52 Elk Prairie (abd. 1940)—Jefferson
53 Ina—Jefferson
54 Whittington—Franklin
55 Benton—Franklin
56 West Frankfort—Franklin
57 Thompsonville—Franklin
58 Mattoon—Coles
59 Siggins—Cumberland, Clark
60 York—Cumberland
61 Hidalgo—Jasper
62 North Boos—Jasper
63 Dundas Consolidated—Jasper, Richland
64 Mason—Effingham
65 Iola—Clay
66 Sailor Springs—Clay
67 Flora—Clay
68 Clay City Consolidated—Clay, Wayne
69 Noble—Richland
70 Olney—Richland
71 South Olney (abd. 1941)—Richland
72 Schnell—Richland
73 Bonpas—Richland
74 Bonpas (West)—Richland
75 Parkersburg—Richland
76 Rinard (abd. 1939)—Wayne

*Name of Pool—County*

77 Johnsonville—Wayne
78 Roundprairie—Wayne
79 Cisne—Wayne
80 Jeff—Wayne
81 Mt. Erie—Wayne
82 S. Mt. Erie—Wayne
83 Boyleston—Wayne
84 Goldengate—Wayne
85 Mayberry—Wayne
86 North Aden—Wayne
87 Aden—Wayne, Hamilton
88 Barnhill—Wayne
89 Leech Twp.—Wayne
90 Bone Gap—Edwards
91 Ellery—Edwards, Wayne
92 Albion—Edwards
93 Cowling—Edwards
94 Grayville—Edwards, White
95 Dahlgren—Hamilton
96 Belle Prairie—Hamilton
97 Bungay—Hamilton
98 Hoodville—Hamilton
99 Rural Hill—Hamilton
100 Dale—Hamilton
101 Walpole—Hamilton
102 Eldorado—Saline
103 Mill Shoals—White, Hamilton
104 Burnt Prairie—White
105 Grayville West—White
106 Centerville—White
107 New Harmony Consolidated—White
108 Calvin—White
109 Phillipstown—White
110 New Harmony South—White
111 Maunie North—White
112 Maunie—White
113 Maunie South—White
114 Stokes—White
115 Carmi—White
116 Storms—White
117 Iron—White
118 Roland—White
119 Herald—White
120 New Haven—White
121 Omaha—Gallatin
122 Inman North—Gallatin
123 Inman East—Gallatin
124 Inman—Gallatin
125 Junction—Gallatin
126 Warrenton-Borton—Edgar
127 Westfield—Clark, Coles
128 Casey—Clark
129 Martinsville—Clark
130 North Johnson—Clark
131 South Johnson—Clark
132 Bellair—Crawford, Jasper
133 Main—Crawford
134 New Hebron—Crawford
135 Flat Rock—Crawford
136 Chapman—Crawford
137 Allison-Weger—Crawford
138 Parker—Crawford
139 Birds—Crawford, Lawrence
140 Russellville—Lawrence
141 Lawrence—Lawrence, Crawford
142 South Lawrence—Lawrence
143 St. Francisville—Lawrence
144 Lancaster—Wabash, Lawrence
145 Allendale—Wabash
146 West Mt. Carmel—Wabash
147 Mt. Carmel—Wabash
148 Maud—Wabash
149 East Keensburg—Wabash
150 Keensburg—Wabash
151 Griffin—Wabash

### CLASSIFICATION MAP.

In September 1930, at the invitation of the Western Society of Engineers, Chicago, the Illinois State Geological Survey prepared an exhibit of the scientific data which it had accumulated during its previous 25 years of activity, on the mineral wealth of Illinois, and the geological-engineering conditions within the State. As a part of this exhibit a map was prepared classifying the State into areas according to the relative probability of finding new oil fields. In this map the Illinois basin and part of the marginal area to the west were given the highest rating. The classification was based mainly on two factors: (1) the presence or absence of strata known to be oil producing, and (2) the varying character of the structural deformations in various regions. Fig. 2 shows the original classification and the location of oil pools as of September 1941.

Among those who attended the conferences and exhibit of the Western Society of Engineers and State Geological Survey in Chicago in September 1930 were representatives of the Pure Oil Company. Having for some time considered the possibilities of the Illinois basin as a productive province, and encouraged by development in Michigan resulting from their early work there, the Pure Oil Company, shortly following this meeting, undertook additional subsurface geological studies of the Illinois basin and then a torsion balance survey across the basin. According to Wasson, "This work, which started at the Indiana line and crossed a portion of the old fields, indicated a gravitational disturbance similar to that found on the south end of the old fields."

Economic conditions necessitated the abandonment of further geophysical investigations for the next few years.

### REFLECTION SEISMOGRAPH.

The key that unlocked the door to hidden oil structures in the Illinois basin proved to be the reflection seismograph method. Encouraged by the success of this method in Oklahoma and Texas, the Pure Oil Company introduced it into Illinois in the

fall of 1935. Following a reconnaissance seismograph survey of a large area in the fall and winter of 1935–1936, the Pure Oil Company acquired a block of leases in April 1936, covering about 250,000 acres in Wayne, Richland, and Jasper counties, and extending approximately from Fairfield on the south to Hunt City on the north. Up to date some 25,000 acres are producing oil in the area of this block. These new fields extend with minor breaks for nearly 35 miles in a northeast-southwest direction.

### STUDIES OF PENNSYLVANIAN STRATIGRAPHY.

The seismograph method, however, was not the only guide to exploration in the Illinois basin. Beginning in 1926, the Illinois Geological Survey began a far-reaching investigation of Pennsylvanian stratigraphy under the direction of J. M. Weller.

Reconnaissance studies by Weller resulted in the formulation of a theory of Pennsylvanian cyclical sedimentation that was tested by H. R. Wanless in the detailed mapping of two western Illinois quadrangles. Later reconnaissance studies by Wanless demonstrated that Pennsylvanian cyclothems, about 50 of which are now recognized in Illinois, can be traced and correlated for long distances. This new approach to the complex problems of Pennsylvanian stratigraphly has made possible the correlation of Pennsylvanian beds and the mapping of small subdivisions of the Pennsylvanian system in great detail. These studies were continued as rapidly as possible by Weller, Wanless, and assistants until all of the Pennsylvanian area in Illinois (about ¾ of the State) had been covered in reconnaissance. Evidence of structures favorable to the occurrence of oil in the basin was uncovered and the results for one of the most promising areas were published by the Survey early in 1936.[4] The report contains a structure contour map on the Omega limestone, which crops out in the area described.

[4] Weller, J. M., and Bell, A. H.: Geology and oil and gas possibilities of parts of Marion and Clay Counties, with discussion of the central portion of the Illinois Basin. Illinois Geol. Surv. Rept. Inv. No. 40, 1936.

Mr. M. W. Fuller, at that time a graduate student in the University of Illinois assisted in field studies of the Pennsylvanian in western and extreme southern Illinois as an employee of the Survey. Following his resignation from the Survey staff in the spring of 1934, Mr. Fuller was employed by the Carter Oil Company and later that year was assigned to studies of the stratigraphy and structure of outcropping beds in the Illinois basin and surrounding areas under the direction of Mr. E. V. Whitwell. Messrs. Fuller and Whitwell independently discovered and mapped the structures described in the Survey report mentioned above. Beginning in the fall of 1935 leases were taken in these and other areas on the basis of geologic studies of outcropping beds.

The pioneering efforts of the Pure Oil Company and the Carter Oil Company in exploring the Illinois basin and in leasing large blocks of acreage were followed by investigations and leasing by numerous other oil companies, both major and independent. Among the companies that undertook geological studies in the area in the fall of 1935 were the Shell Oil Company and the Texas Company. The publication of Report of Investigations 40, by the Illinois Geological Survey March 1, 1936, greatly stimulated interest in the territory. The first deep test wells in the Illinois basin were begun by the Pure Oil Company in the late fall of 1936 and were drilled with cable tools. In the meantime the first well drilled with rotary tools in Illinois was begun by the Adams Louisiana Oil Company, now Adams Oil and Gas Company, near Patoka in late December 1936. This well was located on a coal structure,[5] which was also mapped by seismograph. It came in for a 52 barrel producer from the Benoist sand, depth 1391–1418 feet, January 27, 1937, and was the discovery well of the Patoka pool. The Patoka pool is located on the west margin of the basin about 10 miles north of the old Sandoval pool, and accordingly was not as noteworthy a discovery as the first two wells in the central part of the basin. These were the Pure Oil Company's Weiler No. 1, completed February 26, 1937, as a 40-barrel producer in the

[5] Blatchley, R. S.: Illinois oil resources. Ill. Geol. Surv. Bull. 16, 1910, Pl. 14, opposite p. 142.

Cypress sandstone from 2608 to 2613 feet, the discovery well of the Clay City pool, Clay County, and the same company's Bradley No. 1, completed March 4, 1937, estimated initial production 100 barrels in the Aux Vases (basal Chester) sandstone, discovery well of the Cisne pool, Wayne County.

The first big producer in the Illinois basin was the Pure Oil Company-B. Travis No. 1, the discovery well of McClosky production in the Clay City pool, completed May 15, 1937, for an initial production of 2642 barrels.

Once large scale competitive leasing got under way in the Illinois basin there was little opportunity to use detailed surface geology as a guide to leasing because by the time detailed work could be completed in one area, the land would be leased by competitors. Some companies leased large areas, in some cases almost entire counties, and then began their detailed structural or seismograph investigations, or both. Numerous fields were discovered by a combination of geological and geophysical methods in which the seismograph work was located in an area where surface or coal data suggested the presence of favorable structure. The Louden and Patoka fields are examples of this.

## NEW TECHNIQUES.

New techniques introduced into Illinois in connection with the development in the Illinois basin include rotary drilling, electric logging, and drilling-time logging. Coring and the testing of cores for porosity, permeability and saturation, acidizing limestone pays, cementing casing in wells, the shooting with nitroglycerin of sandstone pays, are among those techniques previously in use in the state but which were greatly expanded during the development of the new fields. Electric logs have proved a great boon both to production men and geologists. Where many wells are being completed in a short time the electric logs provide a ready means of obtaining stratigraphic and structural data important in planning further development. If it were necessary to depend for this upon sample study logs the time necessary to

obtain these data that are needed immediately would be greatly increased.

As has been pointed out by Levorsen in a recent paper,[6] the use of rotary drilling "gave a final and lasting boost to geology." In the old days of cable-tool drilling, logs were made by the driller, but owing to the nature of rotary drilling it is difficult or impossible for the driller to make a good log. Because the services of a geologist are needed to make an adequate log of a rotary well, in the words of Levorsen, "a much closer relationship developed between the geologist and the oil industry with the change of drilling."

In 1926 when the writer joined the staff of the Illinois Geological Survey he knew of only one oil company geologist resident in the State who was actively concerned with Illinois oil geology. Beginning about 1937 there was a rapid increase in the number of oil geologists employed in the State and at present the number is something like 200.

## FUTURE TRENDS IN GEOLOGIC STUDIES.

Having considered the part played by geological theory in beginning the new development in the Illinois basin, let us consider briefly how the new data resulting from this development may influence geological theory and geological studies in the future.

The drilling of more than 13,000 wells for oil and gas in southern Illinois in the past 5 years has provided a wealth of new information on the subsurface geology of the State. The interpretation of these data in terms of geologic history is a formidable task. It is going forward in the offices of many oil companies and in the State Geological Survey. A forum for the discussion of common problems is provided in the monthly meetings of the Illinois Geological Society which is affiliated with the American Association of Petroleum Geologists.

[6] Levorsen, A. I.: Geology and oil discovery. Presented before the Illinois-Indiana Pet. Assoc. at Robinson, Illinois, June 7, 1941.

The fundamental problems of petroleum geology—the origin of oils, their mode of occurrence, migration, and accumulation, the nature and origin of the reservoirs and the reservoir rocks and their contained fluids, etc., will continue to engage the attention and thought of geologists in Illinois as elsewhere. Because a great majority of the oil pools of Illinois are found to be on or near anticlinal structures, efforts have been devoted largely, perhaps too much so, to the search for anticlinal structures. The importance of lenticular sands has been recognized in some areas, for example the old fields of Crawford County, and similar conditions are being revealed in some of the new fields in the Wabash River area. With increased knowledge of subsurface stratigraphy it is to be expected that more effort will be devoted to the search for stratigraphic traps. Although we may not have an East Texas it is quite possible that important oil occurrences under similar geological conditions may yet be revealed.

In conclusion, I should like to quote from a recent paper [7] by Levorsen.

> Thus we see how, as our theories and ideas change, our concept of the undiscovered reserve changes and that it has increased exactly in proportion as our limiting view points were destroyed. And so it goes, with the result that today our mental limitations on what constitutes favorable oil territory are at the lowest in our history and the favorable areas for future possible discoveries the highest.

The Illinois basin is an example of a prolific oil-bearing area where mental limitations in the past prevented exploration. Once these mental limitations were removed its opening could not long be delayed.

ILLINOIS GEOLOGICAL SURVEY,
URBANA, ILL.,
*Nov. 4, 1941.*

[7] Op. cit.

# PRINCIPLES OF SEDIMENTATION AND THE SEARCH FOR STRATIGRAPHIC TRAPS.[1]

W. C. KRUMBEIN.

ABSTRACT.

The need for a more thorough understanding of sedimentary principles has become increasingly apparent as geological exploration for petroleum moves toward the location of non-structural traps. The present paper reviews some of the principles involved in the study of sedimentary environments, and attempts to show that a study of fundamental properties of sediments may prove basic to future exploratory work.

The role of basic research is to explore new paths to knowledge through the evaluation of such fundamental sedimentary parameters as size, shape, roundness, composition, surface texture, and fabric. The relation of these parameters to mass properties such as porosity and permeability needs study, and a knowledge must be gained of conditions that control the lateral and vertical variations of these mass properties in sedimentary environments. From such fundamental studies, indices that are helpful in tracing porosity wedges and flank sands may be developed. In addition to studies of clastic sediments, conditions of formation of non-clastics must be attacked. The role of practical application lies with petroleum geologists, whose task includes the use of the newer principles in exploration, and their further development or discard as exploration continues.

It is emphasized that sedimentary research is only one of several lines of attack on petroleum exploration by geological methods. The closer coordination of paleontologic, stratigraphic, and sedimentary work should insure a continuously expanding frontier in the geological search for oil.

## INTRODUCTION.

THE extensive areas and rich production of such oil fields as East Texas, Midway-Sunset, and Burbank have focussed the attention of petroleum geologists on the outstanding importance of stratigraphic traps in building petroleum reserves. At present such traps seem largely to elude either geological, geophysical, or geo-

[1] Paper presented in the symposium on "Geological Frontiers in the Search for Oil," 50th Anniversary Celebration, University of Chicago, September, 1941.

chemical detection. Certainly the development of geological methods as successful with these new traps as conventional methods became with structural traps is one of the new geological frontiers in petroleum exploration.

Levorsen, in his classic presidential address on the subject,[2] organized present knowledge of stratigraphic traps into three main categories. These traps, he pointed out, may be associated with unconformities, with flank sands on buried structures, or with wedge porosity belts along ancient shorelines. The writer would

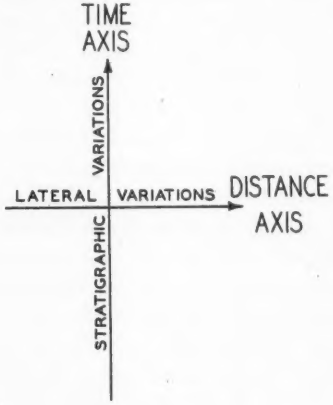



FIG. 1.

like to develop the thesis that stratigraphic traps may be approached from two points of view. These viewpoints may be represented by two arrows, one pointing vertically upward, and the other directed horizontally sideward (Fig. 1). The vertical arrow is a time axis, and concerns geological events as a function of time at some particular point on the earth's surface. The horizontal arrow, on the other hand, is a space or distance axis, and refers to events as a function of distance at any given time. The vertical time axis is studied mainly by stratigraphic methods,

[2] Levorsen, A. I.: Stratigraphic vs. structural accumulation. A. A. P. G. Bull. 20: 521–530, 1936.

because its reconstruction depends upon the sequence of events as shown by the stratigraphic column. The horizontal axis may be studied by sedimentary methods because it involves the lateral gradations within a particular stratum or formation.

In terms of petroleum exploration for stratigraphic traps, the important feature to find along the vertical axis is a stratigraphic break—a point where the time axis apparently shows a discontinuity. Thus for such exploration it is necessary to develop critical indices by which unconformities of any magnitude whatever may be found. Similarly, in terms of the horizontal space axis, an important feature to find for petroleum exploration is a wedge edge of porosity. This may mean developing methods for the location of old strand lines or other sand bodies which grade laterally into siltstone or shale.

A complete discussion of sedimentary research applied to stratigraphic traps should include both aspects represented by these imaginary arrows, but limitations of space prevent such detailed treatment here.[8] Instead, the areal distribution of sediments, and the lateral variations which occur within any environment of deposition will be emphasized, inasmuch as they represent the space relations of the problem.

It is the purpose of this paper to review certain fundamental properties of sediments and to show how a study of these properties may be related to petroleum exploration. Emphasis is placed on quantitative investigations, using concepts that have been developed by sedimentary petrologists largely within the last decade. The approach outlined here is not to be considered as a substitute for all other methods, but rather as a supplement to basic studies by the methods of stratigraphy, paleontology, and the whole background of geological analysis.

## PROPERTIES OF SEDIMENTS.

A single sedimentary basin may have forming within it simultaneously such varied deposits as sand and gravel in the shore

[8] The writer discusses some of the problems associated with the location of unconformities in his paper, Criteria for the Subsurface Recognition of Unconformities. A. A. P. G. Bull 26: 1942. In press.

facies, silt and mud in the quieter off-shore waters, and rich organic muds within lagoons, estuaries, and similar sites. Thus, when the term "environment of deposition" is used in a broad sense, it refers to a complex of many factors that here tend toward the development of one deposit, and there toward that of another. It is not impossible for entirely different environments to produce the same kind of sediment at least locally, nor, as was said, is it unusual for a single environment to produce different sediments in different places. Because of these complexities, heavy mineral analysis, for example, may sometimes be effective in correlating two samples, and in other instances it may not. Similarly, mechanical analysis is of limited value in perhaps a majority of instances. Twenhofel [4] has recently emphasized the fact that one cannot, from a graph of size analysis, reconstruct the conditions under which the sediment was formed.

The recognition of these truths has been somewhat painful to those who work with sediments, but it is becoming increasingly clear that the relations of sediments to their environments are more complex than was formerly thought. What has to be done, apparently, is to break the problem down to its simplest elements, and to study each element in terms of its response to environmental conditions.

What are the simplest elements that can be found? To answer this question, it may be well to return to first principles, and to restate the underlying purposes of sedimentary study. Geologists are interested in sediments in part for the light they shed on such questions as the source of the sediment, the distance of transport, and the nature of the environmental conditions under which the deposit was formed. The basic assumption in these studies is that each sediment is a response to a definite set of environmental conditions, and that the properties of the sediment reflect these conditions to a greater or lesser degree. Reconstruction of an environment of deposition therefore depends upon an interpretation of the attributes of the sediment. What are the funda-

[4] Twenhofel, W. H.: The frontiers of sedimentary mineralogy and petrology. Jour. Sed. Pet., 11: 53–63, 1941.

mental attributes of a sediment that are important in the history of the deposit? Whatever they are, they should be rigorously definable, they should be measurable, and they should be such that other characteristics of the sediment depend upon them, or may be derived from them. Clearly, for clastic sediments at least, it is necessary to consider the particles themselves, to get at the basic characteristics of the sediment.

One of the most important attributes of a sedimentary particle is its settling velocity, because that controls the behavior of the particle in a fluid, whether the particle is settling out, being lifted from the bottom, or simply carried along. The settling velocity, in turn, depends upon the size, shape, and density (mineral composition) of the particle, as well as upon the properties of the fluid. Thus the fundamental attributes here are size, shape, and density, because from them the settling velocity behavior may be derived. If one thus reduces the factors that control the behavior of a particle, or which most clearly are affected by the history of the particle, he arrives at six basic properties of sedimentary grains. These are:

1. Size
2. Shape (sphericity)
3. Roundness
4. Mineral composition (density)
5. Surface texture
6. Orientation

Each of these six properties can be defined in a variety of ways. Size, for example, may be defined in terms of a settling velocity, a sieve mesh, a series of intercepts.[5] Much confusion appears to center about the characteristics of shape and roundness, however, which are frequently considered to be identical. Actually the two concepts are geometrically distinct, as Wadell showed.[6]

[5] Krumbein, W. C., and Pettijohn, F. J.: Manual of Sedimentary Petrography, New York, 1938, pp. 126 ff., and pp. 143 ff.

[6] Wadell, H.: Volume, shape and roundness of rock particles. Jour. Geol., 40: 443–451, 1932; Sphericity and roundness of rock particles. *Ibid.*, 41: 310–331, 1933; Volume, shape, and roundness of quartz particles. *Ibid.*, 43: 250–280, 1935.

The shape of a particle is its form, entirely independently of whether the edges or corners are sharp or blunt. Fundamentally the shape is a measure of the ratio of the surface area of a sphere to that of a particle having the same volume. For practical purposes Wadell defined the *sphericity* as the cube root of the ratio of the volume of the particle to the volume of its circumscribing sphere. The roundness of a particle is a measure of the curvature of the corners and edges expressed as a ratio to the average curvature of the particle, independent of its form. For practical purposes the "average curvature" is expressed in terms of the inscribed circle drawn in a projection of the particle in a plane.[7]

The mineral composition of sediments (or the corresponding lithological composition of larger particles) is expressed in terms of the relative abundance of the various species present. The surface texture of particles is not yet established on a quantitative basis, and hence this attribute is not measurable with present techniques.[8] The orientation of a particle, as the term is used here, refers to the directions of its principal axes with respect to coordinate axes fixed in space; the orientation of the particles in a deposit represents the imbrication or fabric of the deposit. Orientation is destroyed when the particle is removed from its parent deposit, but methods are available for preserving the orientation for laboratory study.[9]

Although every clastic particle has the six properties listed, the study of sediments involves not single particles, but a population of particles composing a stratum or formation. It is common knowledge that all the particles in a given bed are not of the same size, shape, mineral composition, etc., but that they vary to a greater or lesser degree. It is, therefore, necessary to consider each characteristic of the sediment in terms of its own variation within the deposit, or even within a single sample of the deposit. In short, it is necessary to view each of the fundamental character-

[7] For short methods of measuring the sphericity and roundness of particles see Krumbein, W. C.: Measurement and geological significance of shape and roundness of sedimentary particles. Jour. Sed. Pet., 11: 64–72, 1941; and Riley, N. A.: Projection sphericity. Jour. Sed. Pet., 11: 94–97, 1941.

[8] For a discussion of surface texture see W. C. Krumbein and F. J. Pettijohn: *op. cit.*, chapter 12.

[9] Krumbein, W. C.: Preferred orientation of pebbles in sedimentary deposits. Jour. Geol., 47: 673–706, 1939.

istics as frequency distributions having a particular average value, a particular degree of spread (" sorting "), and perhaps a degree of asymmetry (skewness). Thus from the six fundamental characteristics come twelve or more statistical measures, which form the basis for the quantitative evaluation of the sediment.

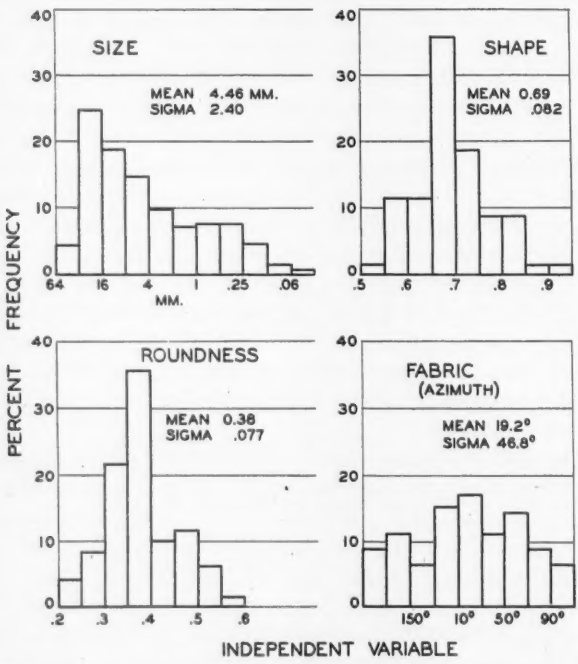



FIG. 2. Size, shape, roundness, and orientation histograms of a sample of flood gravel.

To illustrate that each fundamental attribute has a frequency distribution, Fig. 2 shows the analytical data of a sample of flood gravel from San Gabriel Canyon, California.[10] The several graphs are histograms of the size, shape, roundness, and fabric (axis orientation in space) of the

[10] Krumbein, W. C.: Flood gravel of San Gabriel Canyon, California. G. S. A. Bull. 51: 639–676, 1940. (Sample 4.)

same sample. In each histogram there is a vertical frequency scale and a horizontal scale on which the attribute is plotted. For each distribution there is a mean value and a degree of spread, which are indicated on the graphs.

The size distribution indicates a rather poorly sorted sandy gravel, with a marked skewness toward the smaller sizes. The orientation of the pebble axes is not marked, although there is a preferred orientation toward the northeast-southwest of the longest pebble axes. The shape distribution shows a prominent maximum between 0.65 and 0.70, whereas the roundness of the pebbles is relatively low, with a maximum under 0.40. These last two diagrams, incidentally, indicate the confusion which may arise unless shape and roundness are clearly distinguished in describing the sediment.

The proper interpretation of such a set of diagrams depends upon their relation to adjacent samples collected from the same environment. Details are to be found in the reference cited.

In contrast to the fundamental characteristics of sediments are certain mass properties, such as color, porosity, permeability, plasticity, and shear strength. These mass properties may be measured directly, but they depend upon particular combinations of the fundamental characteristics, modified by such factors as the degree of cementation, the water content, and so on. For example, permeability depends upon both the average size and the degree of sorting, modified by the shape and orientation of the particles in the deposit. Similarly, various structures of the sediment, such as thickness of bedding, or ripplemark, depend upon the behavior of individual particles, or of the transported load, under given dynamical conditions.

## SYSTEMATIC STUDIES OF SEDIMENTARY ATTRIBUTES.

From the preceding analysis it would appear that if attention is focussed on the fundamental attributes of sediments, means should be at hand whereby one by one the complex factors of sediment behavior may be studied. It is not sufficient, however, to analyze a few scattered samples. Instead, the problem must be approached on an environmental scale, and from a dynamical point of view, so that the behavior of each attribute may be seen in terms of the

factors that control it. In general, three approaches seem to be available.

*Environmental Studies of Modern Sediments.*—The fact that sediments are known to vary from point to point within a single environment suggests that detailed quantitative studies be made of such variations in terms of the fundamental attributes of the sediments. This may be accomplished by choosing a modern environment, such as a beach, an estuary, a tidal lagoon, a river drainage basin, etc., and collecting a series of samples from a grid laid over the environment. Each sample is analyzed in terms of the fundamental properties, and maps are made of the distribution of these properties over the environment. For example, a size map may be made by plotting the average particle size of each sample at its corresponding sampling point, and drawing size contours over the area.[11] Such a map would immediately make apparent any systematic lateral variations of size over the environment. A similar map could be made of the degree of sorting, of the heavy mineral content, of the average shape, and so on. Each of these sediment maps yields an "environmental pattern" of the attribute, which sheds light on how that attribute responds to the dynamical processes occurring within the environment. A complete study of this kind would require a simultaneous investigation of environmental processes at each sampling site. In a tidal lagoon, for example, such related studies include the direction and magnitude of currents, the amount of material in suspension, the depth of water, the pH content, perhaps the bacterial content and faunal aspects of the bottom, and so on.

Comparatively few studies of such broad scope have been made, although here and there in the literature are evidences of this line of attack. Perhaps the most comprehensive is Hjulström's study of the River Fyris in Sweden.[12] Not only did Hjulström collect data on the sediments themselves, but he related these to the entire background of source rock, topography, stream

[11] The first suggestion of such maps was made by Trask in 1930. See his Mechanical analysis of sediments by centrifuge. Econ. Geol., 25: 581–599, 1930.

[12] Hjulström, F.: Studies of the morphological activity of rivers as illustrated by the River Fyris. Geol. Inst. Upsala, Bull., 25: 221–527, 1935.

discharge, method of transport (suspension and traction), and so on. Somewhat more common are studies of the sediments within environments, with less quantitative data on processes. As an

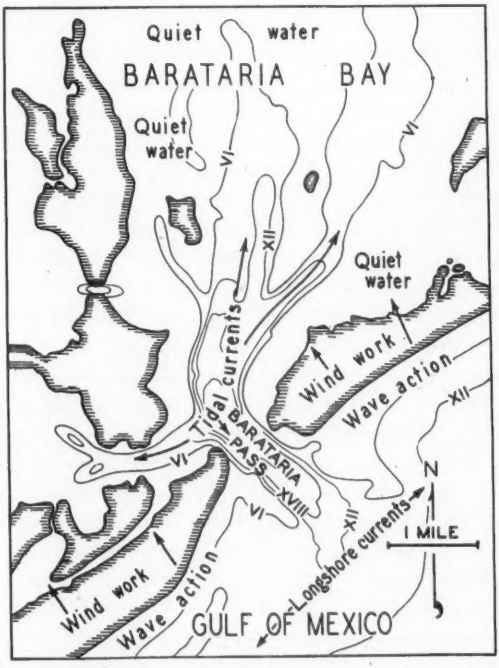



FIG. 3. Map of southern portion of Barataria Bay, Louisiana.

illustration of such environmental patterns themselves, a tidal lagoon will be used, because of its possible bearing on petroleum geology. The example is based on several earlier papers,[13] which

[13] Krumbein, W. C., and Aberdeen, Esther: The sediments of Barataria Bay. Jour. Sed. Pet., 7: 3–17, 1937; Krumbein, W. C., and Caldwell, L. T.: Areal variation of organic carbon content of Barataria Bay sediments, Louisiana. A. A. P. G. Bull. 23: 582–594, 1939; Caldwell, L. T.: Areal variations of calcium carbonate and heavy minerals in Barataria Bay sediments, Louisiana. Jour. Sed. Pet., 10: 58–64, 1940.

may be referred to for additional details. In the present discussion the maps are somewhat simplified and generalized, to emphasize the underlying principles.

Fig. 3 shows part of Barataria Bay on the Mississippi delta. It is bounded by a barrier beach with a tidal inlet. Superimposed on the map are indications of the processes taking place, to show that the environment as a whole is actually a composite of several interrelated environments. A study of the dynamics of the environment [14] should permit a prediction of the kinds of sediments distributed over the bottom. For example, along the beach where waves break and generate a high degree of turbulence, one may expect both the coarsest and best-sorted deposits. Wind work on the barrier may select certain ranges of size and shape to form dunes, as well as to carry sand over the barrier into the lagoon. Along the main channel associated with the tidal inlet there should be selective transportation due to the periodic currents, so that moderately coarse and moderately well-sorted sediments may be expected there. In the shallow waters of the lagoon, away from the channels, fine sediments, rather poorly sorted, and with a moderate amount of organic matter, should predominate. In some instances zones of fine sediments may form along the inner margin of the barrier adjacent to the inlet, due to slow eddies generated by the tidal currents. The general stream lines of such motion are shown in Fig. 4. Submerged offshore deltas may also form as a result of tidal currents.

If it is true that sediments represent definite responses to environmental conditions, the fundamental attributes of the sediments in this environment should indicate the processes going on. That they do is indicated by the four environmental pattern maps of Fig. 5. These maps are based on the analysis of nearly 100 samples collected over the bay. Fig. 5A shows the contours of average size. The coarsest deposits occur along the beach, with some extension bayward due to wind-blown sand. The channels

[14] The following analysis of the dynamics of tidal lagoon environments is generalized from several sources, mainly Johnson, D. W.: Shore Processes and Shoreline Development, New York, 1919, and Interim Report, Beach Erosion Board (office of Chief of Engineers, U. S. Army), Washington, 1933.

contain moderately coarse material, and the size gradually decreases away from the channels toward the low islands in the bay. A " shadow zone " of fine sediments is well developed on the inner margin of the barrier just east of the inlet. Fig. 5B shows a sorting map of the bay. This environmental pattern also brings out the essential features of the environment, and indicates progressively poorer sorting as one leaves the zones of active wave action or the stronger currents. Fig. 5C shows a heavy mineral

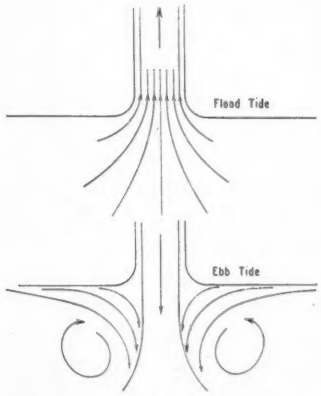



FIG. 4. Theory of tidal currents at inlets. (From Beach Erosion Board Interim Report, 1933.)

content map; again the underlying pattern, with its dendritic extensions from the linear barrier, is brought out. Even non-mineral attributes of the sediments may bring out the pattern, as in 5D, which is a map based on the percentage of organic carbon in the sediments.

In detail the numbers on the contour lines indicate the order of magnitude of lateral changes in the environment. The median map is based on geometrically-spaced contours, so that each contour represents material twice as coarse or fine as the adjacent line. The sorting values may be interpreted directly in terms of Wentworth grades. The value 1.5, for example, means that the middle half of the size distribution has a spread of 3 Wentworth grades. The larger the number, the poorer the sorting.

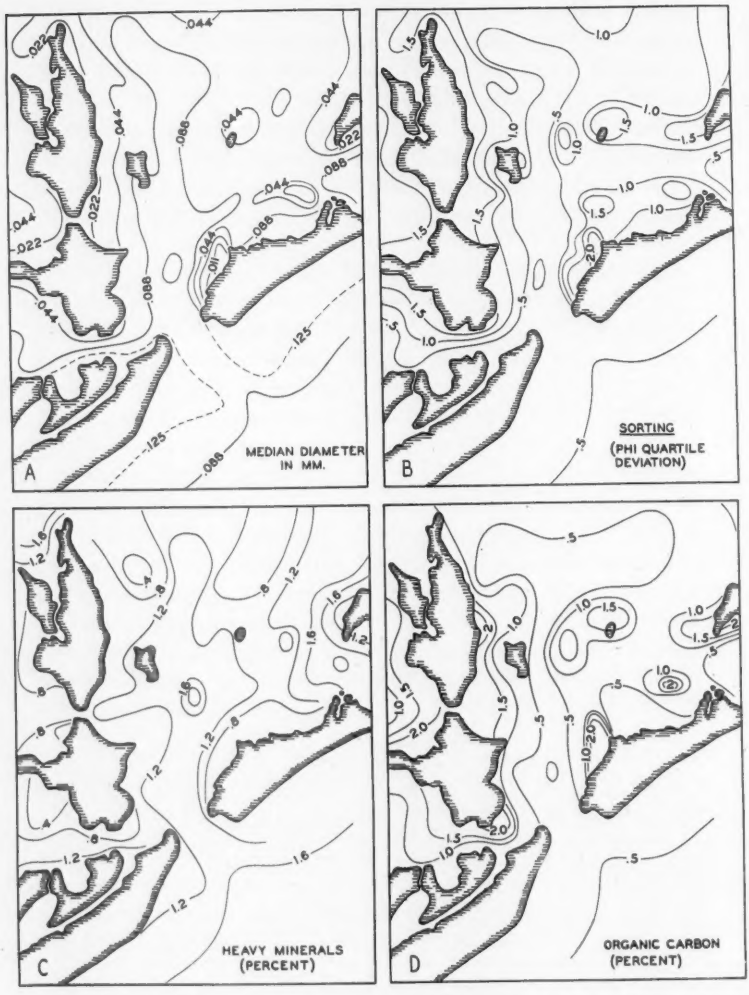



FIG. 5. Environmental patterns of southern part of Barataria Bay, Louisiana.

The heavy mineral map refers only to percentage present; a complete study would involve maps of individual species, of significant ratios, and among ancient sediments, of original and authigenic minerals. The organic carbon map shows only the per cent of organic carbon present; the actual amount of organic material is higher.

These several illustrations indicate that environments do tend to develop patterns that are reflected by the fundamental attributes of the sediment, as well as by some of the mass properties. A systematic study of a series of environments will afford a set of comparative patterns, of value in understanding sedimentary processes. Not only are such patterns of value in developing rigorous principles of sedimentation, but they may also prove helpful in the study of ancient environments. This aspect of their use will be discussed later.

An important by-product of environmental pattern studies is the light shed on problems of correlation. A study of the laws of variation of size, sorting, shape, roundness, heavy minerals, over environments of deposition will indicate not only which ones change systematically in the direction of transport, but it will also indicate how much variation may be expected in a given deposit. Such data are of value in setting up principles of correlation, because they indicate within how narrow or how wide a range the characteristics vary from point to point along their areal extent.

*Laboratory Studies of Particle Wear and Transportation.*—Although a knowledge of the physical conditions within an environment permits a qualitative prediction of the broad characteristics of sediments within the environment, it is not possible to predict just what size range may be expected, or quantitatively just how the shape and roundness, say, vary from point to point. Before this can be done even approximately, the dynamical laws that control the transportation and wear of sedimentary particles under various conditions must be known. The number of variables involved is so great, and their relative importance is so little understood, that recourse must be had to experiment to discover the laws. Fortunately, means are available for such studies, which permit a segregation of the process of wear from that of selective transportation.

Tumbling barrel studies shed light on the importance of particle wear, and flume studies or scale model experiments furnish data on the role of transportation. Considerable work on abrasion has been done by geologists,[15] and hydraulic engineers[16] have made basic contributions to the field of sediment transportation. Unfortunately present generalizations are in many instances too limited to permit direct application to geological field problems, but certain suggestions emerge from the work which have a bearing on sedimentary studies.

At the risk of considerable over-simplification, Table 1 is given here to indicate roughly the relations of abrasion and selective

TABLE 1.

| Property. | Effect of Wear. | Selective Transport. |
|---|---|---|
| Size | × | ×× |
| Shape | × | ×× |
| Roundness | ×× | —* |
| Density | — | × |
| Surface Texture | ×× | — |
| Orientation | ? | ×× |

* Probably negligible, or a second-order term.

transportation to the fundamental properties of sedimentary particles. The importance of each process is indicated qualitatively by symbols—×× indicates relatively large effects, whereas × suggests a moderate effect. A dash indicates a negligible effect, and a question mark indicates an unknown effect. Although numerous qualifications must be included in detail, observational data show that during abrasion both the roundness and surface texture change much more rapidly than size or shape. Presumably the process of wear has no effect on either the density (mineral composition) or orientation. Selective transportation is definitely related to size, shape, and density, because these properties

[15] For a review of abrasion studies on larger particles see Krumbein, W. C.: The effects of abrasion on the size, shape, and roundness of rock fragments. Jour. Geol., 49: 482–520, 1941.

[16] An excellent discussion of the general scope of the problem is to be found in Rouse, Hunter: Fluid Mechanics for Hydraulic Engineers, New York, 1938, chapter 14.

control the settling velocity of the particle. Roundness itself seems to be essentially negligible in comparison with the shape effect, as is surface texture. The orientation of the particle seems to be largely controlled by its shape, and so responds to the dynamical conditions of transportation.

What the table suggests in the main is that roundness and surface texture may be indices of the abrasive history of the particle, whereas the other characteristics may be indicative of the dy-

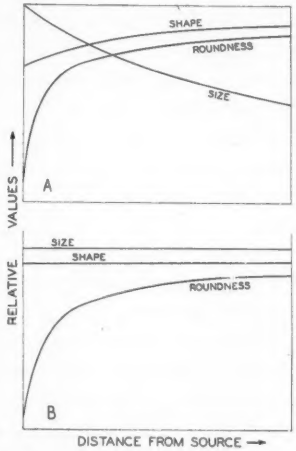



FIG. 6. Relations of size, shape, and roundness to distance from source. *A*, abrasion dominates; *B*, special conditions of transport dominate.

namics of the transporting process, with orientation a clue to the agent involved. The process of wear itself includes several elements, as impact, crushing, and abrasion. The table emphasizes the less vigorous processes. (See reference in footnote 15.)

Many combinations of these several effects may be observed in nature, so that detailed analysis of any given situation is complex. This complexity may be illustrated by two examples. In situations in which abrasion dominates, the size, shape, and roundness would vary in the direction of transport as shown in Fig. 6A.

That is, roundness increases markedly, shape (sphericity) increases slightly, and size decreases slightly. If rapid breakage occurs, size may decrease more rapidly, and even roundness may decrease. When selective transportation controls, the observed changes in the properties may be entirely different. The writer studied flood deposits [17] in which the relations are as shown in Fig. 6B. Here the size and shape responded to essentially fixed dynamical conditions of deposition throughout, and hence showed no marked changes with distance, whereas the roundness increased continuously, and remained a function of the distance travelled (and hence the abrasion suffered) by any particle before it came to final rest. This latter situation is apparently an exceptional combination of events, but it illustrates that one cannot expect simple relations to hold in every instance. It is the writer's present opinion that selective transportation is on the whole of greater importance than abrasion in controlling observed sedimentary variations.

In both the study of modern environments and in the laboratory study of specific processes, a statistical method of attack may prove helpful. Statistical analysis, as it is currently applied, is confined largely to obtaining a series of numbers describing the sediments, but beyond having this tool for description and comparison, little is known of how to interpret the numbers after they are obtained. Actually the calculation of average size, sorting, or average shape, is merely a preliminary, and gives the geometry of the sediments. If these numbers are to be of value, they must be fitted into a background of theory which explains their magnitude and their variations. The manner in which statistical data may be useful in this connection is as follows:

1. Summarizing masses of sedimentary data.
2. Description and comparison of sediments.
3. Evaluation of experimental errors.
4. Study of interrelations among sedimentary properties.
5. Development of quantitative analytical theories of sediment behavior.

There is little doubt that the full use of statistical data lies in the future, especially in connection with the last two items in the table.

[17] Flood gravels of San Gabriel Canyon, California, *op. cit.*

*Environmental Studies of Ancient Sediments.*—The investigation of ancient sediments is much more difficult than that of modern sediments, both because the environment itself has vanished, and because of the changes that may have occurred in the deposit since deposition, including modification by diagenesis, by diastrophism, and the removal of parts of the deposit by erosion. Nevertheless, it should be possible to reconstruct many ancient environments by a method of attack which parallels the study of modern sediments.

In order to determine environmental patterns of ancient sediments, especially in the subsurface, considerable background work is necessary. A particular stratum must be chosen, and it is necessary to know the stratigraphic relations thoroughly, so that one may be certain his samples are from the same horizon. Moreover, unless a large number of cores are available, cuttings must be used, which somewhat limit the data that can be obtained. Even so, it is frequently possible to obtain first approximations to the average size and degree of sorting, as well as average shape and roundness, plus some data on heavy minerals. At least partial patterns can be made, and from the convergence of the several lines of evidence, a fair reconstruction should be possible. If in the meantime environmental patterns were available for a number of modern environments, comparisons with the ancient patterns would suggest possible interpretations of the latter, taking due cognizance of changes due to diagenesis, later erosion, diastrophism, etc. In fact, conspicuous differences between the ancient pattern and its modern counterpart may suggest the nature of post-depositional changes. The work of Smithson on the Estuarine Series (Jurassic) is interesting in this connection.[18] Maps were made of the richness of the heavy mineral suite and of the frequency and grain size of individual species. Some maps reflected the paleogeography at the time of deposition, whereas others brought out the tectonic history of the area. The latter effect was shown by post-depositional changes in the mineral characteristics.

[18] Smithson, F.: Statistical methods in sedimentary petrology. Geol. Mag., 76: 297–309; 348–360; 417–427, 1939.

In its practical applications to petroleum geology, the environmental pattern approach seems to offer two possibilities. It would be of direct interest to petroleum geologists if some known petroliferous region, in which sedimentary conditions control the traps, were studied from the environmental pattern point of view. Cuttings could be re-examined in terms of the fundamental attributes of the particles, as a basis for environmental pattern maps. Upon the resulting patterns could be drawn the known distribution of oil pools, with the result that the optimum associations of oil pools and environmental patterns could be seen. By studying the sedimentary variations on all sides of the known pools suggestions would arise regarding those diagnostic features which vary systematically as the pool is approached. Suppose the pools are governed by "porous spots" in the sand member. Permeability would presumably be the controlling factor, and the dependence of permeability on size and sorting may be reflected by hills or hollows in the corresponding environmental patterns. Other factors, not usually involved in the study of recent sediments, would have to be considered. The permeability may be a function of the degree of cementation. Maps of the percentage of acid-solubles would bring this factor out.[19] With more recently developed fields, electric logs may furnish data on relative permeabilities as a basis for a permeability pattern. Any one of these devices may of course be used individually, but the underlying principles will emerge more clearly if the convergence of several lines of evidence is studied.

Paralleling the pattern study of known petroliferous regions could be systematic exploration of patterns in regions where the paleography and paleogeology suggest favorable conditions for sedimentary and stratigraphic traps. For such explorations outcrop data would be tied in with the subsurface, to obtain at least fragmentary patterns along certain chosen horizons—one would

[19] In this connection see the map of calcium carbonate content in terms of well production by P. D. Torrey, in Problems of Petroleum Geology, A. A. P. G., 1934, p. 474.

naturally use not only the data from the sedimentary particles themselves, but all other surface and subsurface lines of attack. The principal role of the detailed sedimentary studies is to furnish a basis for evaluating the physical aspects of the environment, and to supply a means for extrapolation to given

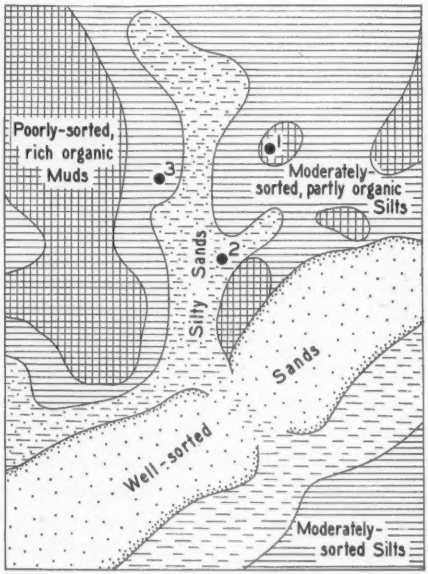



FIG. 7. Generalized pattern of southern part of Barataria Bay, showing location of three hypothetical wells.

distances in given directions. In terms of the hypothetical arrows introduced at the beginning of this paper, the sedimentary studies help to convert the horizontal arrow into a signpost pointing the way to oil.

The manner in which environmental exploration might proceed may be illustrated by the pattern of Barataria Bay. Fig. 7 is a generalized map of the area now considered to be buried under several thousand feet of later sediments. Three wells penetrate

the beds, but the observer knows only what his wells show; the pattern is unknown. Well No. 1 hits the fine organic muds; well No. 2 strikes one of the silt channels, and well No. 3 is in the intermediate shallow zone. If the cuttings are examined it is found that well No. 1 shows black or dark shale, relatively rich in organic matter. Well No. 2 is in a silt-stone, relatively free of organic matter, but on the whole too "tight" for oil production. Well No. 3 is rather nondescript, because it lies betwixt and between. Should one therefore conclude that the region isn't worth prospecting, and move on?

Three wells are not sufficient to establish the environmental pattern, but if the properties of the sediments are examined more closely, one may have a hint of what lies beyond. Note that in terms of a triangle connecting the wells there is an increase in size toward well No. 2 from both the other wells. There is also an improvement in sorting, and a decrease in organic carbon content. Thus one infers a series of slopes in the environmental patterns, with size sloping upward to well No. 2; sorting slopes downward (recall that in measuring sorting, smaller numbers mean better sorting), and organic content slopes downward toward well No. 2.

From the fundamental properties of the particles themselves something may be inferred about mass properties. It is known, for example, that permeability increases as the square of the average particle diameter, and increases with an improvement in sorting. Hence even from the limited knowledge of the environment, it is safe to infer that permeability increases markedly in a general southerly direction. Finally, the decrease in organic carbon toward the south suggests, in combination with the size and sorting, that a strand line lies to the south, with well sorted sand and a high enough permeability to be productive.

Perhaps this illustration is too simple. Certainly problems of correlation enter the picture—one must first be sure that his samples represent the same horizon, and it is to be hoped that subsequent erosion has not swept away the vital part of the environment to the south. Obviously a study of this sort would

supplement and be supplemented by other data. Stratigraphic principles, micropaleontology, general regional history, and the entire background of geological reasoning go along with this approach.

Fundamentally the use of environmental patterns is no radical departure from conventional methods of applying sedimentary data to petroleum exploration. Rea [20] recently suggested that from several slim-hole prospecting wells it may be possible to reconstruct sedimentary trends, and thus to predict the most promising directions for further exploration. The present viewpoint merely quantifies such an approach, and suggests its use on a regional basis, using the entire basin of deposition, or at least its more marginal aspects, as the unit for study. Even the idea of an environmental pattern is not new; the pattern of sediment thickness has been used extensively—it is the familiar isopach map. It may not be too far-fetched to call a structural contour map an environmental pattern, but it may be a pattern not so much of the original sedimentary environment as of the subsequent diastrophic environment. Torrey's calcium carbonate map, mentioned earlier, is an environmental pattern of post-depositional cementation.

*The Problem of the Non-Clastics.*—The foregoing discussion has emphasized clastic sediments. Equally important are the non-clastics, especially limestones, but their interpretation on the basis of rock characteristics is much more difficult than with clastics. This added difficulty arises partly from the fact that limestone is fundamentally different from the clastics in the dynamics of its formation. Whereas clastics are carried into the environment as mechanically transported solids, limestone usually forms right in the depositional basin through the operation of complex biological and chemical processes. The greater susceptibility of limestone to recrystallization and other diagenetic changes adds to the difficulty of unravelling its past history, because during such alterations both texture and structure may be

[20] Rea, H.: Applied sedimentology. A. A. P. G. Bull. 25: 899–901, 1941.

modified. Trask [21] investigated the factors that control the proportion of calcium carbonate in sediments, and showed that the basic factor is the precipitation of calcium carbonate from sea water. This single factor itself involves the laws of dynamic chemical equilibrium, and is affected by numerous controls. Trask analyzed some of these controls, and found that the degree of salinity of the sea water is important. In terms of modern sediments, high salinity is generally associated with deposits rich in calcium carbonate. Trask concludes that it is premature to attempt the rigorous reconstruction of the environments of ancient calcareous sediments until the laws governing the formation of modern deposits are known. He does show, however, that it is possible to apply some of the findings of the dynamic study, as in the evaluation of ancient climates in terms of the calcium carbonate content of sediments.

As in the case of clastic sediments, then, a pressing need is a greater understanding of the physical, chemical, and biological controls of sedimentation during the formation of limestone. Even so, it may be possible to obtain useful knowledge about ancient limestones by areal studies of certain presumably diagnostic features. Maps of the areal distribution of insoluble residues, such as that made by Trainer [22] on the Tully limestone, give an insight into the amount and kind of clastic material associated with the limestone. Maps based on the calcite content of calcareous sandstone or shale may throw light on original gradations from one type of rock to the other, or they may merely reflect the cementation history of the deposits. Finally, the areal variation of the magnesium content of limestone or of the associated chert nodules may be of value in studying original vs. secondary processes. The point is merely that until such studies are made one cannot predict whether the data will be of value or not.

[21] Trask, P. D.: Relation of salinity to calcium carbonate content of recent sediments. U. S. Geol. Surv. Prof. Pap. 186–N, 1936.

[22] Trainer, D. W.: The Tully limestone of central New York. N. Y. State Museum, Bull. 291, 1932.

SUMMARY.

In the final analysis, the rigorous application of sedimentary data to petroleum exploration seems to depend upon a thorough knowledge of present-day sedimentary phenomena. This knowledge in turn apparently depends upon the acquisition of quantitative knowledge about sediments within environments of deposition, analyzed in the light of physical, chemical, and biological factors which control the processes. If the sum total of such knowledge is cast up, some surprising gaps are discovered. For example, such fundamental things as the law of variation of sediment thickness with distance from source, the laws of size, shape, and roundness variations from source, and the exact relation of mass properties, such as porosity and permeability, to the fundamental characteristics of sediments, are to a large extent unknown. What data are available on such questions is frequently contradictory. The laws of areal variation of sediments over present-day environments; the characteristics of particular environments; the changes in sedimentary character from lagoonal or estuarine conditions to the open sea; criteria by which a strand line may be certainly identified; and many other basically important questions apparently still await an answer.

The practical demands of petroleum work essentially rule out an attack on these problems by oil geologists themselves, and the time and expense involved usually remove them from the realm of individual university research. Co-operative research, as exemplified by the basically important work of Trask under the auspices of the American Petroleum Institute, seems to offer the best opportunities. The pure research geologist, aided by chemists, physicists, and biologists, should extend the frontiers of knowledge regardless of the immediate practical bearing of the research. A group of liaison men representing petroleum exploration may apply promising leads, and either perfect them into exploration techniques, or discard them as exploration proceeds.

In the meanwhile, despite the paucity of quantitative data, much work can be done individually by studying areal variations of sedimentary properties over chosen environments, both ancient and

modern. The interrelations disclosed by such studies are not only useful in themselves, but they pave the way for more dynamic studies by suggesting possible causal relationships, some of which may then be tested under controlled laboratory conditions. Among ancient sediments a closer integration of the methods of stratigraphy, paleontology, and sedimentary petrology will go far in extending the practical value of these subjects to the exploration for stratigraphic traps.

UNIVERSITY OF CHICAGO,
CHICAGO, ILL.,
*Nov. 4, 1941.*

# GROUND-WATER TEMPERATURE ON LONG ISLAND, NEW YORK, AS AFFECTED BY RECHARGE OF WARM WATER.

M. L. BRASHEARS, JR.[1]

ABSTRACT.

Ground water generally is more economical than surface water for cooling purposes because of its lower temperature. Because of favorable conditions on Long Island, many supply wells have been drilled for cooling purposes. The water table in an area of 45 square miles in western Long Island was below sea level in 1933. In order to prevent further overdevelopment, the New York State Water Power and Control Commission has required that ground water pumped for cooling purposes from wells constructed since 1933 be returned to the ground. The amount of recharge during the cooling season has increased from about ½ million gallons a day in 1933 to 30 million gallons a day in 1940. The temperature of the water returned to the ground ranges from 2 to 20 degrees higher than the temperature of the water pumped from the ground. The return of warm water causes a rise in ground-water temperature and this decreases the advantage of using ground water for cooling purposes. The U. S. Geological Survey has observed ground-water temperatures periodically at about 350 wells since 1936. The return of warm water has caused a rise of water temperature as much as 20 degrees at some of the pumping wells. The observations show that a gradual rise of ground-water temperature has occurred in a considerable part of western Long Island.

## INTRODUCTION.

GROUND water is more economical than surface water for air-conditioning and industrial cooling purposes because of its lower temperature during the cooling season. Normally, on Long Island the temperature of ground water is perhaps 15 degrees cooler than surface water that is furnished by public water supply systems. According to Suter [2] the cost of obtaining water from the

[1] Published by permission of the Director of the U. S. Geological Survey.

[2] Suter, Russell: Engineering report on the water supplies of Long Island. New York State Water Power and Control Commission Bull. GW-2: 44, 1937.

public water supply systems on Long Island is about eight times as great as the cost of pumping a privately owned well. Furthermore, the relatively small cost of installation and operation of a ground-water air-conditioning system permits a more or less satisfactory degree of comfort cooling at establishments that otherwise could not economically use the other available methods of air cooling.

The widespread occurrence of highly permeable water-bearing sands and gravels at fairly shallow depths on Long Island has, therefore, resulted in the installation of ground-water air-conditioning and industrial cooling systems at many restaurants, theaters, stores, and other business establishments.

In 1933 the ground-water level in an area of about 45 square miles, comprising most of Kings County, was below sea level.[3] This condition was caused by overdevelopment of the water-bearing sands and gravels underlying the western end of the Island. During 1933 the New York State Legislature, recognizing the seriousness of this overdevelopment, passed a law requiring that the approval of the State Water Power and Control Commission be obtained before constructing a ground-water supply plant with a capacity of more than 100,000 gallons a day. Since the passage of the law the policy of the Commission in most cases has been to require water pumped from new wells for cooling purposes to be returned to the ground so that additional overdevelopment from new wells would essentially be prevented. The Commission generally requires that water be returned to the same formation from which it is pumped. As a result of the Commission's requirements a large number of recharge wells (locally called diffusion wells) have been drilled. However, ground-water levels have continued to decline in parts of western Long Island since 1933. In 1936 the area in which the water table was below sea level was somewhat greater than in 1933.[4]

[3] Thompson, D. G., Wells, F. G., and Blank, H. R.: Recent geologic studies on Long Island with respect to ground water supplies. ECON. GEOL., 32: Fig. 7, p. 467, 1937.

[4] Suter, Russell: op. cit., Fig. 26, p. 49.

A typical ground-water air-conditioning system consists of a supply well from which relatively cool water is pumped. The water, after passing through a series of air cooling coils is returned to the ground by means of a recharge well. In the larger air-conditioning systems and most of the industrial cooling plants, ground water is also used to cool refrigeration machinery. The water is returned to the ground from air-conditioning and cooling plants with an increase in temperature ranging from about 2 to 20 degrees. Plants that use ground water to cool refrigeration machinery generally return the water to the ground with a greater temperature rise than air-conditioning and cooling plants of other types.

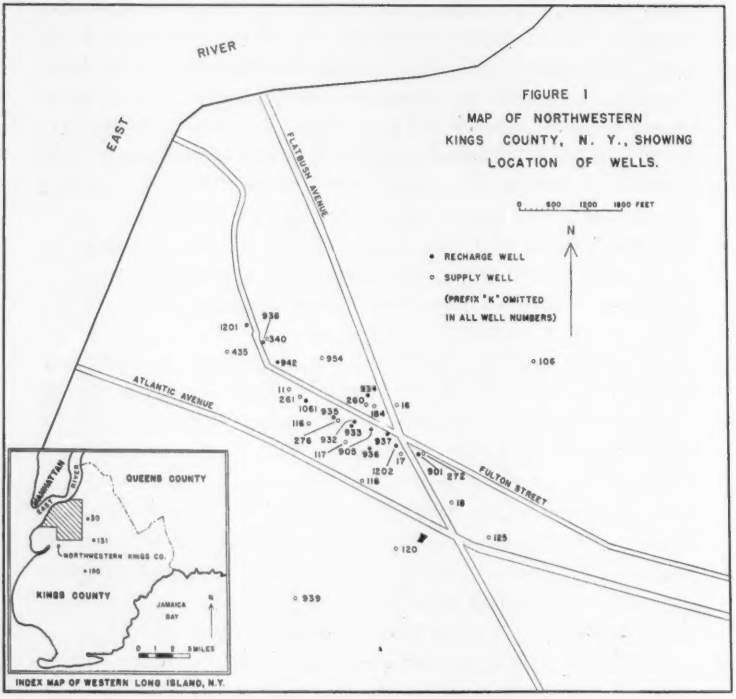
The return of warm water to the ground causes a rise in temperature of the water in the ground and this decreases the advantage of using ground water for cooling purposes. The increased cost of operation resulting from such temperature rises is considerable in some instances.

In 1936 the U. S. Geological Survey began a program of periodic observations of ground-water temperature in about the western half of Long Island. These observations soon indicated that recharge of warm water had locally caused a rise of ground-water temperature at many places on western Long Island.[5]

Most of the recharge wells in western Long Island are located relatively far apart. However, in several areas the density of wells and rate of recharge is relatively high. The most concentrated recharge occurs in an area of about ¼ square mile in northwestern Kings County (Fig. 1), where about three million gallons of water was returned to the ground daily during the summer of 1940. The water table is below sea level in all of this small area of concentrated recharge.

*Geology and Ground-water Conditions.*—Long Island is a part of the northernmost extension of the Atlantic Coastal Plain. It is composed of unconsolidated sediments resting unconformably on a basement of metamorphic rocks of pre-Cambrian and early

[5] Leggette, R. M., and Brashears, M. L., Jr.: Ground water for air-conditioning on Long Island, New York. Am. Geophys. Union Trans., Part 1, pp. 412–418, 1938.




Paleozoic age. The lower portion of the sediments consists of a considerable thickness of deposits of Cretaceous age overlain in most places by a relatively thin mantle of Pleistocene glacial deposits.[6]

The bedrock is composed principally of gneiss containing some intrusions of granite and diorite and some infolded dolomitic limestone of early Paleozoic age. These rocks crop out only in a small area along the East River. The surface of the bedrock slopes to the southeast about 100 feet to the mile.

The lower part of the Cretaceous beds, considered to be of Raritan age, is composed chiefly of clay that overlies an extensive

[6] Thompson, D. G., Wells, F. G., and Blank, H. R.: op. cit., Fig. 1 and 2, p. 454.

bed of water-bearing sand and gravel, the Lloyd sand. The upper part of the Cretaceous, believed to be of Magothy age, consists largely of very fine silty sand containing numerous relatively thin beds of clay. Several widespread beds of water-bearing sand and gravel occur in the Magothy, especially in the lower part. The Cretaceous sediments crop out only at a few places along the north shore and at some of the hills in the center of the Island. These beds dip to the southeast at about 75 feet to the mile.

The Pleistocene beds lie unconformably on the Cretaceous. In parts of western Long Island the Cretaceous deposits have been entirely removed by erosion and the glacial deposits lie on the bedrock or its weathered equivalent. The lower part of the Pleistocene consists of the highly permeable water-bearing Jameco gravel and beds of the Gardiners clay and Jacob sand. The Gardiners clay, which overlies the Jameco outwash gravel, grades conformably into the overlying Jacob sand. The Gardiners and Jacob beds are interglacial deposits and are believed to have been laid down during the Yarmouth interglacial stage. The early glacial deposits are distributed around the borders of Long Island and also lie in most of the buried valleys that were cut in the underlying Cretaceous deposits at the western end of the Island. The uppermost sediments on Long Island, considered to be of Wisconsin age, consist chiefly of outwash sand and gravel and till. The upper glacial beds cover most of the Island and are the chief source of ground water on Long Island.

Nearly all the ground water used for industrial purposes and air-conditioning in Kings and Queens Counties is obtained from the uppermost Pleistocene outwash deposits. Most of the warm water that is returned is discharged into these beds. Ground water occurs chiefly in an unconfined condition in the outwash deposits. However, the beds of sand and gravel are interspersed with thin layers and lenses of clay and silt that confine the ground water at some places.

In the area of about ¼ square mile, lying on both sides of Fulton Street (Fig. 1) where artificial recharge is most concentrated, bedrock lies approximately 100 feet below sea level. In

this area the Cretaceous beds have been removed by erosion and the bedrock is overlain in most places by glacial outwash considered to be of Wisconsin age.[7] In the southeastern part of this ¼ square mile area the outwash gravels are apparently underlain by a thin remnant of Gardiners and Jacob clay and silt. Well logs and borings indicate that the glacial beds in the vicinity of Flatbush Avenue and Fulton Street constitute essentially a single water-bearing zone from which water is withdrawn and to which water is returned. However, thin relatively impervious zones occur in the water-bearing material between the horizons at which the different wells are screened. Such zones probably delay the movement of warm water from recharge wells to supply wells and this results in a much slower rise of temperature than if no such zones existed. These impervious zones and other small irregularities of stratification not recorded in well logs may account for some of the temperature anomalies that have been observed.

*Ground-water Levels and Pumpage.*—The overdevelopment of the ground-water resources in the western part of the Island has caused the water table to decline considerably below sea level in most of Kings County and in western Queens County and a "crater-like" depression has been formed. The lowest part of the "crater" is located in the northern part of Kings County. During 1940 the fluctuation of water level in well K 30 (see Fig. 1 in which the prefix "K" has been omitted in all well numbers to avoid crowding the map), at one of the lowest observed parts of the "crater," ranged from about 28 to 29 feet below sea level. The water level near some of the pumped wells in the lowest parts of the "crater" was somewhat lower than at well K 30. The water table in most of Kings County and in a considerable part of Queens County slopes toward the lowest parts of the "crater." It is apparent, therefore, that any warm water returned to the water-bearing beds within the "crater" or in the areas where the water table slopes toward it will tend to flow toward the center of the "crater." Moreover, this warm water will remain in the "crater" until it is removed by pumping. Elsewhere on Long

[7] Thompson, D. G., Wells, F. G., and Blank, H. R.: op. cit., Fig. 4, p. 461.

Island the water table generally slopes toward the shore, and warm water returned to the water-bearing beds is, for the most part, eventually discharged into bodies of sea water that surround the Island.

The estimated net withdrawal (withdrawal minus recharge) in the ¼ square mile area of most concentrated recharge (Fig. 1) was about 3,000,000 gallons a day during the summer of 1940 and about 1,500,000 gallons a day during the rest of the year. This withdrawal of water caused a local depression of the water table of considerable extent in this small area. Relatively cool water is continuously moving into this depression where it mixes with the warm water discharged from recharge wells. A part of this mixture is removed by pumping wells that discharge into sewers. The rise of ground-water temperature in this area depends largely on the temperature and amount of the cool and warm water. Because of the irregular distribution and operation of recharge wells and supply wells, the direction and rate of flow of ground water in this area is variable. It is apparent, therefore, that these conditions would produce irregular changes of ground-water temperature especially during cooling seasons.

*Recharge Wells.*—A recharge well may be defined as any well that returns water to the ground. The flow of water in a recharge well is in the opposite direction to that of a supply well. Thus, in the area surrounding the recharge well, a cone of elevation is formed on the water table. The cone of elevation is similar in form to the cone of depression that is produced around a pumping well, except that the apex of the cone is above the water table. If a supply well and a recharge well are close together, as is the case at many Long Island installations, the cones of elevation and depression overlap and some of the water discharged from the recharge well will be drawn into the supply well. The rate of this flow of water depends chiefly on the distance between the wells, the hydraulic gradient, and the physical properties of the water-bearing material. If a considerable quantity of warm water is drawn into a supply well the efficiency of the cooling plant may be considerably reduced. For example, at an industrial plant

in Kings County, which continuously recharges about one million gallons daily, the temperature of the water pumped from the supply well increased about 20 degrees after a few months of operation. The supply well and recharge well both end in the same formation and are about 200 feet apart. It is reported that this rise in temperature increased operating costs about 300 to 500 dollars a month. To reduce the cost of operation the supply well was deepened, after which water with about the original temperature was obtained.

Several types of recharge wells have been constructed on Long Island since the first wells were drilled and much progress has been made in improving methods of construction. Some of the earlier wells were merely pits that ended above the water table. These usually proved unsuccessful because of excessive clogging and incrustation and the screens of most of the wells now being constructed are placed below the water table. Recharge wells are usually drilled as distant from the supply wells as size of property and hydrologic conditions will permit, so that the rise of ground-water temperature at the supply well will be kept at a minimum. The general practice at the present time is to place the screen of the recharge well a short distance below the water table and that of the supply well in the lower portion of the same bed of water-bearing material. Recharge wells of the gravel walled type have been constructed at some installations.

Recharge wells and the surrounding water-bearing material gradually become clogged due to silting and incrustation. This decreases the capacity of the well, and the efficiency of the well and the cooling system of which it is an integral part is gradually reduced. To prevent excessive clogging, most drillers subject both the recharge and the companion supply well to a considerable period of development. If only a small amount of silt is present in the water pumped from the supply well, the total quantity that is discharged into the recharge well during one air-conditioning season may be considerable. Apparently the rate at which recharge wells become clogged depends largely on the amount of development to which the supply well is subjected and the physical

properties of the water-bearing material. Some wells become clogged during a single season of operation but most of them continue to pass the required amount of water for several seasons. Most clogged recharge wells have been restored to approximately the original capacity by bailing and redevelopment.

Table 1 gives estimates of the number of recharge wells in operation and the quantity of recharge in Kings and Queens Counties during the past eight years. About 75 per cent of this recharge occurred in Kings County.

TABLE 1.

ESTIMATED RECHARGE OF GROUND WATER IN KINGS AND QUEENS COUNTIES, N. Y.

| Year | Number of Recharge Wells in Operation.[a] | | Recharge in Gallons a Day. | |
|---|---|---|---|---|
| | Air-conditioning Season. | Non-air-conditioning Season. | Air-conditioning Season. | Non-air-conditioning Season. |
| 1933 | 2 | 2 | 486,000 | 478,800 |
| 1934 | 11 | 2 | 1,402,800 | 478,800 |
| 1935 | 25 | 4 | 3,585,600 | 1,234,800 |
| 1936 | 58 | 13 | 14,862,000 | 5,366,400 |
| 1937 | 93 | 15 | 21,256,200 | 6,091,650 |
| 1938 | 109 | 17 | 25,188,600 | 6,475,650 |
| 1939 | 128 | 18 | 28,366,200 | 6,547,650 |
| 1940 | 142 | 18 | 30,531,000 | 6,547,650 |

[a] Excluding wells used temporarily for dewatering purposes during sub-surface construction.

During 1940, 124 of the recharge wells in operation were used in conjunction with air-conditioning systems. The remaining 18 recharge wells were operated during most of the year for the return of water used in cooling plants and the manufacture of ice. At some of the larger industrial and air-conditioning plants as much as 1,000 gallons a minute was used during the summer of 1940.

*Ground-water Temperature.*—The natural ground-water temperature is fairly constant throughout the year in most areas where the water table is not too near the land surface. Usually this temperature is within a few degrees of the average annual air temperature. The mean annual air temperature at the western

end of Long Island is about 52 degrees and the natural temperature of ground water ranges from about 52 to 56 degrees. Under natural conditions an equilibrium exists in a ground-water reservoir between the amount of heat received from the interior of the earth and the amount of heat lost to the atmosphere. When recharge of warm water takes place, this equilibrium is disturbed and a local rise of ground water and earth temperature occurs. The rate and amount of this rise depends on a number of complex and variable factors, such as quantity of recharge, temperature of returned water, distribution of recharge wells, the physical properties of the water-bearing material, its permeability and continuity both vertically and horizontally.

Anticipating a probable rise of ground-water temperature as a result of large quantities of warm water recharge, the U. S. Geological Survey, in 1936, began a program of periodic observations of ground-water temperature in about the western half of Long Island. This work is a part of the ground-water studies that are being made on Long Island in cooperation with the New York State Water Power and Control Commission, and with Nassau and Suffolk Counties. At the present time observations of ground-water temperature are being made at 347 supply wells and 25 recharge wells. The temperature at 81 of the supply wells and at 5 of the recharge wells is being observed monthly. During the summer, bi-weekly observations are made at about 30 of these wells. Observations at the other wells are made three times a year, usually in April, in August or September, and in December. Some of the observation wells are located near recharge wells but many of them are in areas where no warm water is being returned to the water-bearing beds.

The temperature observations are made with calibrated 16-inch mercury thermometers, graduated in tenths of a degree, from 30° to 80° F. The readings are made with a magnifying tube that is held at right angles to the stem of the thermometer by a spring clamp. After the pump has been operated for a considerable time, a sample of water is drawn from a petcock on the discharge pipe, in most cases less than five feet from the pump. The yield of

most of the supply wells that are sampled ranges from about 70 to 1,000 gallons a minute. The water sample is taken in a standard one-quart thermos bottle that has previously been thoroughly rinsed with the water to be sampled. The thermometer is then lowered into the thermos bottle and the temperature observed. The air temperature at the place of sampling is also observed but no correction is made for emergent stem, as this generally amounts to only about 0.01° F. Tests made to determine the extent to which the water sample is insulated by the thermos bottle indicate that no noticeable change in temperature takes place until after about ten minutes have elapsed. Some of the wells are operated automatically and at the time of sampling it is not known how long the pump has been operating. Observations at these wells may be either higher or lower than the true temperature of the ground water.

Observations of ground-water temperature on Long Island have been obtained for a period of about four years. Thus far, only certain general features are apparent but as the period of record becomes longer, slowly moving trends will doubtless become more evident.

The return of warm water has caused a rise of ground-water temperature in the vicinity of all recharge wells near which observations have been made. The amount of rise of temperature apparently varies chiefly with the rate of recharge, the temperature of the recharge water, and the length of the period of operation. Most of the wells operate only during the air-conditioning season, from about June to September. The ground-water temperature in the vicinity of these wells rises during the period of operation and declines during the rest of the year. However, the rise of ground-water temperature during each air-conditioning season has generally been somewhat greater than the decline during the non-operating period, and a progressive rise of temperature has therefore occurred. Some of the recharge wells are operated during the entire year and as a result, a general rise of ground-water temperature has occurred near these wells. After a considerable period of continuous operation the ground-water

temperature in the vicinity of these wells tends to approach a new equilibrium. Thereafter, the temperature varies with the rate of operation, but it is at all times maintained considerably above the original ground-water temperature.

A rise of ground-water temperature of considerable lateral extent has been observed at a few localities on Long Island where there is concentrated recharge. In the ¼ square mile area in northwestern Kings County a slight rise of ground-water temperature has occurred at a distance of about one half mile from the center of recharge. In most places recharge wells are located relatively far apart and in these areas an appreciable rise of temperature has been observed only at nearby supply wells. A decline in temperature has occurred at some wells that had previously shown a rise. This presumably is due to a decrease in the amount of warm water returned, either because of clogging of the recharge well or because of a decrease in the rate of plant operation.

The average temperature of ground water withdrawn from a considerable number of supply wells in Kings and Queens Counties is given in Table 2. The data shown in the second column of the table are based on wells located relatively distant from centers of recharge. The data shown in the third column are based on wells that are operated only during the summer and that are located near recharge wells into which they discharge. Temperature data for supply wells located in or relatively near areas of concentrated recharge have not been included in the table.

The rise of ground-water temperature shown in Table 2 represents the general effect caused by recharge. The number of wells on which the last column of the table is based increases from 12 in 1936 to 58 in 1940. It is believed that the temperature rise indicated for the 4-year period would have been somewhat greater if all 58 wells had operated throughout the period.

A rise in average temperature of the water withdrawn from supply wells in areas distant from recharge is indicated in the second column in Table 2. About half of the 97 wells included in the 1940 average are in Kings County, where the amount of

recharge was about three times greater than in Queens County. The average ground-water temperature in 1940 based on the Kings County wells was 56.4 degrees F. or about 0.4 degree F. higher than the average for the wells in Queens County. A considerable part of the small rise of temperature during the 4-year period can be attributed perhaps to the cumulative excess of mean air temperature during the four years (Fig. 2). However, the fact that the average temperature at wells in Kings County is higher than at wells in Queens County indicates that part of the rise of temperature during this period was caused by recharge.

TABLE 2.

AVERAGE GROUND-WATER TEMPERATURE IN PARTS OF KINGS AND QUEENS COUNTIES, NEW YORK.

| Year. | Average Ground-water Temperature at End of Air-conditioning Season, in Degrees F. | |
|---|---|---|
| | At Supply Wells Located Distant from Recharge Wells. | At Supply Wells Located Near Recharge Wells. |
| 1936 | 55.7 | 56.8 |
| 1937 | 55.9 | 57.6 |
| 1938 | 56.0 | 58.8 |
| 1939 | 55.9 | 58.7 |
| 1940 | 56.2 | 58.9 |

The graph for air temperature shown in Fig. 2 is based on records at New York, for the period 1871 to 1939, inclusive. The graph shows the cumulative departure from mean monthly air temperature since January 1936. It is apparent that the mean monthly air temperature has been considerably above normal during the period since observations of ground-water temperature were begun.

The cumulative departure from mean monthly air temperature during the air-conditioning seasons of 1936 to 1939, inclusive, ranged from + 2.2 to + 6.7 degrees. During the same season in 1940 there was a deficiency of 3.2 degrees. Thus, in general, there was less need for cooling operations during 1940 than in the preceding four years. A lowering of ground-water temperature as a result of such a decrease in the rate of recharge during the

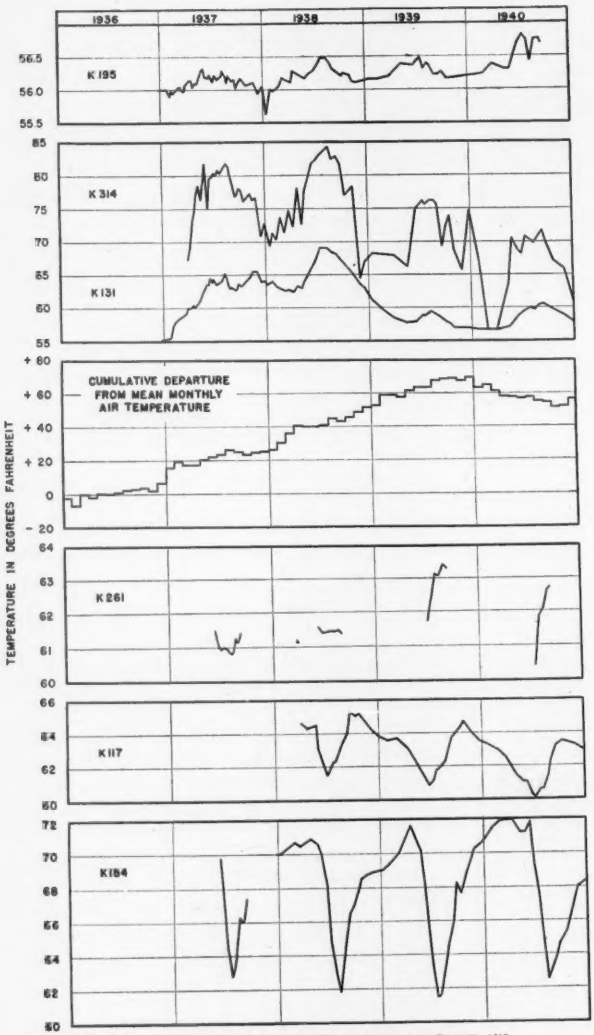



FIG. 2 TEMPERATURE OF GROUND WATER IN KINGS COUNTY, N.Y., AND CUMULATIVE DEPARTURE FROM MEAN MONTHLY AIR TEMPERATURE AT NEW YORK, N. Y.

air-conditioning season of 1940 seems to have occurred only at areas of concentrated development. In northwestern Kings County the temperature of eight of the 15 wells at which temperature observations were made was somewhat lower at the end of the 1940 cooling season than at the same time in 1939.

The temperature graph for supply well K 195 is shown in Fig. 2. This well is operated throughout most of the year for cooling purposes in the manufacture of ice, but warm water is not returned to the ground. About 1,200 feet north of well K 195 there are four recharge wells within an area of about 300 by 600 feet. Since 1936, these wells have been operated only during the air-conditioning season, with an estimated combined recharge of about 460,000 gallons a day. Although the rise of temperature at well K 195 during each air-conditioning season is slight, the graph indicates a gradual rise from year to year as a result of this recharge. During the summer of 1939, a recharge well located about 325 feet northeast of well K 195 began operating at a rate of about 300,000 gallons a day. A noticeable rise of temperature at well K 195 as a result of this air-conditioning operation did not occur until the summer of 1940.

Fig. 2 shows the temperature graphs for supply well K 131 and recharge well K 314. The wells are about 300 feet apart and are located more than a mile from the nearest recharge well. These wells are operated throughout the year chiefly for cooling purposes in the manufacture of ice. As would be expected, because of varying operating conditions, the temperature graph for the recharge well is more irregular than that of the supply well. The recharge well began operating about December 1936. During 1937 and part of 1938 the rate of recharge was about one million gallons a day. By July 1938, this recharge had produced a net rise of water temperature of almost 14 degrees at the supply well. During 1938 manufacturing operations were reduced and the rate of recharge dropped to about 200,000 gallons a day. This rate of recharge has been maintained since 1938, except during February 1939, when the recharge well was cleaned. By the end of 1940, the decrease in rate of recharge at this plant had caused

a net decline of temperature of more than 11 degrees at the supply well. The temperature at the supply well seems to be affected fairly rapidly by sustained changes in the temperature and amount of returned water. In general, the temperature at well K 131 appears to be affected to a greater extent by the rate of recharge than by the temperature of the returned water.

TABLE 3.

DATA FOR SUPPLY WELLS IN NORTHWESTERN KINGS COUNTY, NEW YORK.

| Well Number. | Altitude of Bottom of Well Below Sea Level (Feet). | Estimated Average Daily Yield During 1940 in Gallons a Day | | Distance to Nearest Recharge Well (Feet). | Temperature of Ground Water at End of 1940 Air-conditioning Season (°F.). | Net Change of Ground Water Temperature During 1940 Air-conditioning Season (°F.). |
|---|---|---|---|---|---|---|
| | | Air-conditioning Season. | Non-air-conditioning Season. | | | |
| K 11 | 61 | 24,000 | 24,000 | 250 | 60.5 | +0.2 |
| K 16 | 61 | 504,000 | 0 | 550 | 60.0 | −1.2 |
| K 17 | 65 | 585,600 | 0 | 200 | 61.6 | +1.2 |
| K 18 | 66 | 162,000 | 0 | 1,100 | 58.9 | −0.7 |
| K 116 | 48 | 180,000 | 180,000 | 450 | 59.8 | −0.1 |
| K 117 No. 2 | 62 | 330,000 | 0 | 150 | 75.2 | +11.1 |
| K 117 Nos. 3 and 4[a] | 56 | 252,000 | 210,000 | 300 | 63.2 | +2.1 |
| K 118 | 63 | 36,000 | 36,000 | 600 | 57.5 | −0.1 |
| K 120 No. 2 | 63 | 720,000 | 504,000 | 1,800 | 59.9 | +0.2 |
| K 184[a] | 65 | 210,000 | 0 | 300 | 64.7 | −7.1 |
| K 260 | 69 | 126,000 | 0 | 400 | 65.2 | +6.1 |
| K 261[a] | 25 | 243,000 | 0 | 200 | 62.7 | +2.8 |
| K 272 | 57 | 189,000 | 0 | 150 | 67.7 | −0.2 |
| K 276 | 72 | 554,400 | 302,400 | 100 | 62.1 | −2.3 |
| K 340 | 72 | 207,000 | 0 | 150 | 69.5 | +2.0 |
| K 435 | 38 | 9,000 | 9,000 | 700 | 59.6 | +0.3 |
| K 954 | 44 | 50,400 | 25,200 | 750 | 59.0 | 0.0 |

[a] See graph shown in Figure 2.

Tables 3 and 4 give data for supply wells and recharge wells in northwestern Kings County.

Fig. 1 shows the location of recharge wells and most of the supply wells in the area of most concentrated recharge in northwestern Kings County. It is apparent from the distribution of wells in this area that a rise in temperature in any one supply well may be the result of recharge from a number of adjacent wells. It is estimated that the average daily recharge from all wells in

this area during the 1940 air-conditioning season was about three million gallons. During the remainder of the year the recharge was about 350,000 gallons a day.

Fig. 2 shows the temperature graphs for well K 117 and well K 184. The graphs indicate that a rise of temperature does not take place until a month or so after the beginning of the air-

TABLE 4.

DATA FOR RECHARGE WELLS IN NORTHWESTERN KINGS COUNTY, NEW YORK.

| Well Number. | Altitude of Bottom of Well Above (+) or Below (−) Sea Level (Feet). | Estimated Average Daily Recharge During 1940, in Gallons a Day. | |
|---|---|---|---|
| | | Air-conditioning Season. | Non-air-conditioning Season. |
| K 901 | −55 | 189,000 | 0 |
| K 905 | −38 | 111,000 | 0 |
| K 932 | [a] −60 | 330,000 | 0 |
| K 933 | [a] −60 | 330,000 | 0 |
| K 934 | −26 | 126,000 | 0 |
| K 935 | −55 | 554,400 | 302,400 |
| K 936 | −10 | 264,000 | 0 |
| K 937 | −23 | 180,000 | 0 |
| K 938 | + 6 | 207,000 | 0 |
| K 942 | −24 | 150,000 | 0 |
| K 1061 | −55 | 243,000 | 0 |
| K 1200 | −41 | 72,000 | 0 |
| K 1201 | −15 | 60,000 | 48,000 |
| K 1202 | −30 | 108,000 | 0 |

[a] Previously incorrectly reported as 103 feet below sea level. See Leggette, R. M., Brashears, M. L., Jr., op. cit., table 3, p. 416.

conditioning season. This lag is characteristic of most supply wells in northwestern Kings County, although the period of lag ranges considerably. The drop in temperature at well K 184, which begins each spring, is probably the result of cool water being drawn into the area at the time when industrial pumping is increased. Well K 184 operates only during the air-conditioning season whereas well K 117 operates throughout the year. This and other reasons doubtless cause many of the differences in these two graphs.

The temperature graph of well K 261 (Fig. 2) illustrates clearly the effect caused by the return of warm water to the ground. During 1937 and 1938 the water withdrawn from this

well, after being used to cool air-conditioning machinery, was discharged to the sewer. A recharge well (K 1061) located about 200 feet distant, was drilled during the spring of 1939 and since then has been in operation during the summers. Prior to the installation of this recharge well, there was little or no net rise of temperature at well K 261 during the operating season. However, during the last two years, a rise of about 2 degrees has occurred each season.

*Conclusions.*—The ground-water temperature in the vicinity of most of the areas of recharge in western Long Island is gradually rising from year to year. Thus, an equilibrium between the amount of heat added to the ground by recharge and the amount of heat lost to the atmosphere has not been reached and a further general rise of ground-water temperature is to be expected. The rise of ground-water temperature and its lateral spread is proceeding slowly and probably will continue for a considerable period of time. The rate and amount of temperature rise will be determined in large part by the distribution of recharge wells and the amount and temperature of warm water returned to the ground.

At the present time an appreciable rise of ground-water temperature has occurred only in the vicinity of centers of recharge, although a fairly widespread warming of small extent seems to have occurred.

The rise of ground-water temperature has considerably decreased the advantage of using ground water for cooling purposes at a considerable number of air-conditioning and industrial plants on western Long Island, by causing a decrease in plant efficiency and an increase in operating costs.

U. S. Geological Survey,
Jamaica, N. Y.,
*June 11, 1941.*

# DISCUSSION AND COMMUNICATIONS

## *GRANITE AND ORE.*

Augustus Locke, in his article "Granite and Ore"[1] raises a challenging question. If many bodies of "granite" are in reality metamorphosed sediments rather than magmatic intrusives, whence came the metals to form the associated ore deposits?

Since the appearance of Locke's paper, Grout[2] has injected a note of caution into the present trend toward ascribing metamorphic origin to "igneous-looking rocks" and his keenly analytical review reveals gaps in some of the evidence for conversion of sediments into granite. Nevertheless, many geologists (and I am one of their number) are hospitable to the idea that sediments can be changed into rocks that look like granite (and very possibly over large areas), although we feel the need of further investigation before we shall know where to draw the line in a particular area between metamorphic granite (if any) and magmatic granite (if any).

Assuming, then, if only for the sake of discussion, that certain large bodies of granite are metamorphic in origin, the agencies that might have accomplished this metamorphism, may profitably be considered. All of these agencies have undoubtedly been taken into account by Locke, yet he does not appear to attach great weight to certain considerations which, to me at least, seem important.

Everyone would agree, no doubt, that temperatures must have been relatively high. Temperature due to simple depth might be high enough, although it could hardly account for wide

[1] Econ. Geol., 36: 448–454, 1941.

[2] Formation of igneous looking rocks by metasomatism. G. S. A. Bull. 52: 1525–1576, 1941.

local variations in intensity of metamorphism. Heat due to friction has been advocated, but the verdict that it is capable of producing high temperatures under geological conditions is by no means unanimous. In any case, heat, and even melting temperatures are not in themselves sufficient, for a dry melt of the composition of granite does not crystallize into granite in the absence of a "mineralizer." But given a solvent, quartz, feldspar, mica and hornblende can crystallize. Hence the solvent plays an important role in the process.

Furthermore, if the solvent is present, these minerals can crystallize below the fusion point of any common rock. Hence, although temperatures were undoubtedly high it is not necessary to assume that they reached the melting range or that an appreciable quantity of rock was liquid at any one time. The semblance of viscous flow is not evidence of melting, for it is well known both from laboratory and from geological evidence that rocks can accommodate themselves to extreme deformation by recrystallizing in the solid state in the presence of solutions. For a parallel, consider areas of marble that must have remained essentially solid throughout deformation yet they possess structures that might easily be mistaken for the results of viscous flow: porphyroblasts and "inclusions" in parallel orientation, extreme stretching, and apparent pulling apart of beds.

But even heat and a solvent are not enough. If "metamorphic granites" were merely mud that has been recrystallized without addition or removal of chemical constitutents there would be no difficulty in distinguishing such metamorphic products from rocks of truly magmatic origin. A chemical analysis would tell the story, for granite differs notably in composition from mud. To name only one conspicuous difference, granite contains more soda than does either mud or any plausible combination of sediments.

For these and other potent reasons, most advocates of the metamorphic origin of granite visualize the process as a metasomatic replacement brought about by solutions from a mag-

matic source. Such solutions can supply heat, serve as a solvent, bring in the required chemical constituents and, if necessary, carry away excess material.

According to this view the process would differ from familiar hydrothermal rock alteration in only two essential particulars: first, it might be of wider extent than ordinary zones of wall-rock alteration, and second, the temperature and pressure would be higher, so that instead of the usual sericite, chlorite and carbonates, the stable minerals would be orthoclase, plagioclase, muscovite, biotite and hornblende.

From this point of view the metasomatic alteration of a sediment to "granite" would be visualized as an early, super-intense type of wall-rock alteration. Ore deposits would be regarded as later, cooler and, commonly, satellitic phases of the same process. Is there not here a "reasonable genetic alliance" between metamorphic rock and ore? Given heated aqueous alkali-bearing solutions of magmatic origin, one need look no further for ore solutions. Whether they obtained their metals from the sediments (shades of lateral secretion!) or from that "heiroglyph of an unknown something in the depths of the crust," the magma chamber, may be difficult to determine. To borrow Locke's own phrase, "What would constitute proof?" This (to quote McLaughlin [3]) expresses "a tendency to push the source of the metal-bearing solutions to depths that are safely out of reach." Yet even around true intrusives this sometimes seems unavoidable.

In brief, I submit that granitization requires the introduction, probably of heat, probably of a solvent, and certainly of chemical constituents, notably soda; that the most plausible source of these constituents is a magma; and that if no magma is visible it becomes virtually imperative to postulate one—an underlying magma of regional proportions if you like.

I willingly admit that to postulate such a magma is a very different thing from proving its existence yet its presence rather than its absence is implied by a theory that attributes metamorphic

[3] McLaughlin, D. H.: Mining Geology. Min. and Met. (annual review), Jan., 1940, p. 5.

origin to the granite. The search for a local source of metals should receive all encouragement but one should not loose sight (and I am sure that Locke has not done so) of the availability of an "abysmal source" of ore solutions even though the predominant constituents of the granite may be of local origin.

H. E. McKinstry.

University of Wisconsin,
Madison, Wis.,
*November 1, 1941.*

# REVIEWS*

**The Mining of Gems and Ornamental Stones by American Indians.** By SYDNEY H. BALL. Pp. xii + 77; Plates 5. Anthropological Papers, No. 13, *Bulletin* 128, Bureau of American Ethnology, Smithsonian Institution, 1941.

Economic geologists and mineralogists interested in the development of their sciences will find this excellent paper a veritable storehouse of information concerning the use our American Indians made of gems and ornamental stones and the methods they employed in obtaining them. By searching out this information, which is so widely scattered through the literature, and organizing it in a very readable form, and supplementing it with an exhaustive bibliography of 18 pages, Dr. Ball has also rendered a great service to all students of American Indian cultures.

That primitive man made large use of rocks and minerals is well known. When Europeans first arrived in America, they found that the American Indian, living largely in the stone age, was no exception, for he was familiar with certain metals, gems, and ornamental stones. Dr. Ball asserts that before coming in contact with the white man, no less than 84 gems and ornamental stones were used by the American Indian. This assertion is based upon a careful study of artifacts, mine workings, early and present-day literature, and traditions and myths.

The first 19 pages of the paper contain an excellent summary in which such topics as the uses, sources, ideas of origin, methods of mining of, as well as trade in gems and ornamental stones are discussed. The Indian as prospector, geologist, and mineralogist, and early Indian mining laws are among the other topics treated. There then follows a rather detailed description of the various gems and ornamental stones mined by the Indian, which covers 37 pages. This discussion is well documented by references to the articles listed in the bibliography. There is also a very helpful table giving the occurrences by countries of the various materials discussed. Mention must also be made of three plates illustrating placer mining by the Indians of Georgia, the Los Cerrillos open cut, and the mining of catlinite pipestone in Minnesota. Most helpful are the two

* Books noted under *Reviews* and *Books Received* may be ordered through the Economic Geology Bookshop, W. S. Bayley, Urbana, Ill., but orders for official reports and single copies of Journals should be sent directly to their publishers.

plates of maps of North and South America showing the location of the mines worked by the Indian prior to the coming of the white man.

This exhaustive and painstaking contribution is a most worthwhile addition to Dr. Ball's already long list of publications dealing with the history of gems and of early mining methods. It should prove very helpful, especially to mineralogists and geologists in assisting archaeologists who are studying Indian cultures but who are unfamiliar with the identification and early uses of gems and ornamental stones.

EDWARD H. KRAUS

**Fortunes in Minerals—Simple Tests and How to Make Them.** By ION L. IDRIESS. Pp. x + 128. Angus and Robertson Ltd., Sydney and London, 1941. Price, $2.50.

As its title indicates this little book describes "the different kinds of country and the combinations of rocks in which valuable minerals are likely to occur, and shows how, with the most meagre and inexpensive equipment [the prospector] may discover wealth if he keeps his eyes open."

The book was written for the man who knows little about minerals or chemistry, but it nevertheless describes satisfactory simple blowpipe and chemical tests for nearly all minerals of value and describes also the rocks in which these minerals may be found. The descriptions are clear and easily understood and the directions for applying the tests are given in detail sufficient for the purposes of the prospector.

The volume should be of value to the mineral explorer untrained in chemistry. It should help him in the search for ores and the determination of their contents. However, there are in it several statements which are misleading such as "the Canadian nickel deposits are in granitic country." Moreover, the book might be of more use if its index were enlarged to include references to definitions of reef, lode, and other forms of deposits and if brief descriptions of gabbro and other important rock names were given.

As a whole, the book should be welcomed by explorers and prospectors.

W. S. BAYLEY.

**Mining Engineers' Handbook,** 3rd Edit. Edit. by ROBERT PEELE AND JOHN A. CHURCH. 2 vols.; Pp. 3515. John Wiley and Sons, New York, 1941. Price, $15.00.

This well known "bible of the mining industry" has emerged in a third edition in new form and substance. An inch has been added to the length and breadth of the type page; the page size is now 5.4 × 8.4; and it is in two volumes. The change in size is a decided improvement.

The new edition has been entirely reset and largely rewritten by 62 experts, and all sections contain changes. Many new contributors appear. There are new sections on Geophysical Prospecting and Petroleum Production, and the backbone of the book "Prospecting, Development and Exploitation of Mineral Deposits" (640 pp.) has been largely rewritten and is abreast of the rapid changes in mining. The voluminous illustrations include a host of new ones.

All phases of mining and mineral deposits are treated in the 3500 pages, and in addition are included engineers' tables and the elements of civil, mechanical, and electrical engineering needed by the mining and metallurgical engineer. This monographic work is invaluable to every student and operator in mining and metallurgy; it is a necessary reference to those associated with the mineral industry, and it should be in the library of every economic geologist.

ALAN BATEMAN.

**Outlines of Historical Geology**, 4th Edit. By CHARLES SCHUCHERT AND C. O. DUNBAR. Pp. 291; Figs. 106. John Wiley and Sons, New York, 1941. Price, $2.50.

This edition is a condensation and junior companion of the new 1941, 4th edition of the larger volume on Historical Geology, which is Part II of the Textbook of Geology, a review of which appeared in the July number of this JOURNAL.

This abridgement is written frankly for the student who wishes a brief general survey of historical geology. It presents the record of each era as a unit instead of by periods. The arrangement is in three parts, Prologue, Earth's Changing Features, and The Pageant of Life. The chapters of Part I depart from previous arrangements and the Geologic Time Chart is brought into the first chapter. The Paleogeographic maps of the second part were newly made especially for this edition, and several new illustrations appear. This volume, like its predecessors, is clearly presented, well illustrated and very readable.

**Outlines of Geology.** Physical Geology, 2nd Edit. By LONGWELL-KNOPF-FLINT. Pp. 381; Figs. 281. Historical Geology, 4th Edit. By SCHUCHERT-DUNBAR. Pp. 291; Figs. 176. John Wiley and Sons, New York, 1941. Price, $4.00.

This volume is a combination under one cover of "Outlines of Physical Geology," reviewed in the October number of this JOURNAL, and of "Outlines of Historical Geology," just off the press and reviewed above. They are combined in this form to make a one volume textbook to meet the demands of some teachers for a brief treatise covering the salient parts of both subjects.

**Crater Lake. The Story of its Origin.** By HOWEL WILLIAMS. Pp. 101; Pls. 10; Figs. 9. Univ. of California Press, Berkeley, 1941.

In his introduction the author writes, "Perhaps geology has no more significant lesson to teach than this: all landscapes are evanescent," and proves his statement in the first part of the book by reconstructing the long history of the formation of Mount Mazama and its subsequent decapitation to create the caldera of Crater Lake.

The second part of the book, The Evidence, is considerably less interesting to the reader because of a tiring device used to impart the information. It consists of conversations of a group of people, during various trips on and around the lake, with a Ranger Naturalist of the Park Service. He monotonously asks and answers questions to bring out facts the author wishes to prove his points.

## BOOKS RECEIVED.

WILLIAM E. BENSON.

**The Geology of New Jersey.** J. V. LEWIS AND H. B. KÜMMEL, rev. by H. B. KÜMMEL. Pp. 182; pls. 2; figs. 15; geol. index map in color, scale, 1:1,000,000. New Jersey Geol. Surv., Bull. 50. Trenton, 1940. *Revised edition of Bull. 14, 1914. Handbook of the geology of the state valuable to both geologist and layman.*

**New Jersey Geodetic Control Survey Bench Marks.** Pp. 128. New Jersey Geol. Surv., Bull. 53. Trenton, 1941. *Lists benchmarks established in Burlington, Monmouth, and Ocean Counties.*

**Scientific Survey of Porto Rico and the Virgin Islands, Vol. III—Pt. 4. The Tertiary Foraminifera of Porto Rico.** J. J. GALLOWAY AND C. E. HEMINGWAY. Pp. 210; pls. 36; figs. 1; tables 4. New York Acad. Sci. New York, 1941. *Thorough treatise of the subject with many excellent detailed illustrations. Lists 81 new species.*

**Spirit Leveling in Texas.** J. G. STAACK. U. S. Geol. Surv., Bull. 883, parts B and C. Washington, 1941. Price, 15 cents per part.

883–B. **Part 2. Panhandle, 1896–1939.** Pp. 95; pls. 1; figs. 2.

883–C. **Part 3. West-Central Texas, 1896–1938.** Pp. 85; pls. 1; figs. 2.

**Spirit Leveling in Michigan, 1896–1938.** J. G. STAACK. Pp. 511; pls. 3. U. S. Geol. Surv., Bull. 919. Washington, 1941. Price, 65 cents.

**Phosphate Investigations in Florida, 1934–1935.** P. V. ROUNDY. Pp. 77; pls. 9; figs. 21; tables 28. U. S. Geol. Surv., Bull. 906–F. Washington, 1941. Price, 30 cents. *Prospecting and classification of phosphate areas. New recovery methods permit saving of fines.*

**Geology of the Upper Tetling River District, Alaska.** F. H. MOFFIT. Pp. 41; pls. 6; figs. 2; geol. map in color, scale 1″=4 miles. U. S. Geol. Surv., Bull. 917–B. Washington, 1941. Price, 50 cents.

**Geology and Mineral Resources of the Randolph Quadrangle, Utah-Wyoming.** G. B. RICHARDSON. Pp. 52; pls. 6; figs. 2; geol. map in color, scale 1:125,000. U. S. Geol. Surv., Bull. 923. Washington, 1941. Price, 55 cents. *Phosphate rock is the chief mineral resource.*

**Manganese Carbonate in the Batesville District, Arkansas.** D. F. HEWETT AND H. D. MISER. Pp. 94; pls. 10; figs. 9; geol. map in color, 18″ × 29″, scale 1:62,500. U. S. Geol. Surv., Bull. 921–A. Washington, 1941. Price, 60 cents.

**Geophysical Abstracts 102, July–September, 1940.** W. AYVAZOGLOU. Pp. 32. U. S. Geol. Surv., Bull. 925–C. Washington, 1941. Price, 10 cents.

**The Mineral Industry of Alaska in 1939.** P. S. SMITH. Pp. 97; pls. 1; figs. 3; numerous unnumbered tables. U. S. Geol. Surv., Bull. 926–A. Washington, 1941. Price, 20 cents.

**Some Quicksilver Prospects in Adjacent Parts of Nevada, California, and Oregon.** C. P. Ross. Pp. 15; pls. 3; figs. 1. U. S. Geol. Surv., Bull. 931–B. Washington, 1941. Price, 25 cents.

**Canada Dept. Mines and Resources, Geol. Surv. Paper 41.** Geologic Maps of various parts of Canada sometimes accompanied by short reports. Ottawa, 1941. Price, 10 cents per area. A continuation of Geol. Paper 40 which was first listed in this journal March–April, 1941. The following have been received.

No. 41–1. **MacKay Lake Area, Northwest Territories.** J. F. HENDERSON. Prelim. Map and Report. Pp. 6.

No. 41–2. **Great Slave Lake to Great Bear Lake, Northwest Territories.** Prelim. Map.

No. 41–3. **Ingray Lake Map Area, Northwest Territories.** C. S. LORD. Prelim. Map and Report. Pp. 12.

No. 41–4. **Brazeau, Alberta.** B. R. MACKAY. Prelim. Map.

**Federated Malay States, Report of the Geological Survey Dept. for 1940.** E. S. WILLBOURN. Pp. 14. Kuala Lumpur, 1941. *Confidential Report.*

**Limestone and Lime.** G. I. WHITLATCH. Pp. 34; tables 4. Tenn. Geol. Surv., Markets Cir. No. 10. Nashville, 1941. Price, 10 cents. *Another in this excellent series of short informational papers. Concise treatise of general subject followed by section on lime in Tennessee.*

**Federated Malay States, Chamber of Mines. Six Short Reports on Mining Areas in Malaya.** Kuala Lumpur, 1941. *Reprint from 1940 Year Book.*

**Forty-Second Annual Report of Mining Industry of Idaho.** A. CAMPBELL. Pp. 247. Idaho Bur. Mines and Geol. Boise, 1941. Report for 1940.

**Report of the Committee on the Measurement of Geologic Time.** A. C. LANE, J. P. MARBLE, AND OTHERS. Pp. 141. National Research Council, App. G. of Ann. Rept. Washington, 1940.

**U. S. Geol. Surv.** Several New Bulletins in the Series Entitled **Geophysical Abstracts.** Price, 10 cents per copy.
**Geoph. Abst. 99**; Oct.–Dec., 1939. Washington, 1940.
**Geoph. Abst. 100**; Jan.–March, 1940. Washington, 1941.
**Geoph. Abst. 101**; April–June, 1940. Washington, 1941.

**Pre-Cambrian Geology and Mineral Resources of the Delaware Water Gap and Easton Quadrangles, New Jersey and Penn.** W. S. BAYLEY. Pp. 96; pls. 5; figs. 4; geol. map in color, 14″ × 24″, scale 1:62,500. U. S. Geol. Surv., Bull. 920. Washington, 1941. Price, 40 cents.

**Geology and Ground-Water Resources of the Lufkin Area, Texas.** W. N. WHITE, A. N. SAYRE, AND J. F. HEUSER. Pp. 56; pls. 2; figs. 2; numerous well logs. U. S. Geol. Surv., W. S. P. 849–A. Washington, 1941. Price, 30 cents.

**Effect upon Ground-Water Levels of Proposed Surface-Water Storage in Flathead Lake, Montana.** R. C. CADY. Pp. 21; pls. 8. U. S. Geol. Surv., W. S. P. 849–B. Washington, 1941. Price, 35 cents.

**Analyses of Washington Coals.** H. F. YANCEY, M. R. GREER, AND OTHERS. Pp. 78; figs. 1; tables 19. U. S. Bur. Mines, Tech. Paper 618. Washington,1941. Price, 15 cents. Supplement to Tech. Paper 491. *Describes improvements in mining and handling of coal in the state since 1929, besides giving new analyses.*

**Mining Methods and Costs of the Lava Cap Gold Mining Corporation, Nevada City, Cal.** J. W. CHANDLER. Pp. 18; figs. 14; tables 5. U. S. Bur. Mines, Inf. Cir. 7164. Washington, 1941. *Well illustrated with diagrams of various apparati.*

**California Journal of Mines and Geology, Quarterly Chapter of State Mineralogist's Report XXXVII.** Pp. 193; figs. 30; maps 2. Cal. Dept. Nat. Res., Mines Div., vol. 37, No. 1. Sacramento, 1941. *Includes sections on chromite deposits and detailed study of mineral resources of Trinity County.*

**Canada Dept. Mines and Resources, Report of Mines and Geology Branch for Fiscal Year ended March 31, 1940.** Pp. 49. Ottawa, 1941.

**Nelson Map-Area, East Half, British Columbia.** H. M. A. RICE. Pp. 86; pls. 2; figs. 2; geol. map in color, 11″ × 17″, scale 1″ = 4 miles. Canada Dept. Mines and Resources, Geol. Surv. Memoir 228. Ottawa, 1941. Price, 25 cents. *General, Structural, and economic geology.*

**Ground Water in Keith County, Nebraska.** L. K. WENZEL AND H. A. WAITE; sections on power and irrigation by E. E. HALMOS AND G. E. JOHNSON. Pp. 65; pls. 8; figs. 2; geol. map in color, scale, 1:125,000. U. S. Geol. Surv., W. S. P. 848. Washington, 1941. Price, 70 cents.

**The Diamond Industry in 1940.** S. H. BALL. Pp. 16. Jewelers' Circular-Keystone. New York, 1941. *Complete account of distribution, mining, cutting, and consumption of diamonds throughout the world.*

**Fineness of Gold from Alaska Placers.** P. S. SMITH. Pp. 121; pls. 1; maps 1. U. S. Geol. Surv., Bull. 910–C. Washington, 1941. Price, 30 cents.

# SOCIETY OF ECONOMIC GEOLOGISTS

*Abstracts of Papers to be Presented at the Twenty-Second Annual Meeting in Conjunction with the Geological Society of America, Boston, Mass., December 29–31, 1941.*

## *THE "OPALITE" TYPE OF QUICKSILVER DEPOSIT.*[1]

ROBERT G. YATES AND RALPH J. ROBERTS.

(Introduced by Clyde P. Ross)

Recent studies of the United States Geological Survey in connection with the Strategic Minerals Investigations have revealed that most of the deposits of the "opalite" type are not, as formerly believed, surficial deposits of siliceous hot spring sinter, but were formed by silicification of permeable ash, tuff, sedimentary beds, and, more rarely, of other rocks. Examples of such deposits are in the Opalite district mainly in southeastern Oregon, the National, Ivanhoe, Goldbanks and other districts in Nevada, the Weiser district in Idaho, and less well known districts in other localities.

The opalitic deposits are, in general, nearly flat-lying tabular bodies, which rudely conform to bedding, but some extend along steep fault zones. The opalite is dominantly composed of chalcedony with minor quantities of opal and quartz, and may be dense, porous or a recemented breccia. Cinnabar, intimately mixed with silica, occurs in fractures, cavities and along lines of microbrecciation as well as disseminated in the massive rock.

It is believed that the deposits were formed at shallow depths and that the depth of deposition was controlled by ground water level. The existing rock was first replaced by opal which either dehydrated to chalcedony or was replaced by that mineral. Cinnabar was deposited from siliceous water after the major silicification was concluded. Locally clay minerals were formed, in part at least, after the major silicification but before much of the cinnabar had crystallized. In a few places calcium carbonate formed during a final stage of thermal activity.

## *SCHEELITE-POWELLITE MINERALS OF THE SEVEN DEVILS DISTRICT, IDAHO.*[1]

R. S. CANNON, JR. AND F. S. GRIMALDI.

During a recent study of the geology of the Seven Devils district by the Geological Survey in cooperation with the Idaho Bureau of Mines and Geology, minerals having the physical appearance of scheelite have been found in most of the pyrometasomatic copper deposits. Analyses made in

[1] Published with the permission of the Director, U. S. Geological Survey.

the Chemical Laboratory of the Geological Survey indicate that these minerals are not pure calcium tungstate, but members of the isomorphous series whose end members are scheelite (calcium tungstate) and powellite (calcium molybdate). Minerals of this series which were deposited during the pyrometasomatic copper-tungsten-molybdenum mineralization range in composition from 98.7 per cent of scheelite (percentage by weight of calcium tungstate) with 1.3 per cent of powellite to 13.6 per cent of scheelite with 86.4 per cent of powellite. Other minerals of this series nearer powellite in composition are probably supergene. Certain physical properties of these minerals are approximately linear functions of the composition. Thus, specific gravity and color of fluorescence afford some quantitative basis for estimating the tungsten content.

## *SOME CONCEPTS OF THE GEOLOGY OF QUICKSILVER DEPOSITS IN THE UNITED STATES.*[1]

CLYDE P. ROSS

Quicksilver deposits are widely distributed in the western United States and are diverse in form and wall rocks; however, the valuable bodies are alike in that they contain few and generally simple introduced minerals and are localized where structural conditions favored the introduction of dilute and chemically weak solutions under slight to moderate pressure. Commonly concentration was aided by structural traps high in the ore channels. Deposition was in geologically shallow zones but was not limited to the few hundred or few score feet of vertical range within which ore shoots in many mines are confined. The broader, limiting features of structure can generally be detected rather readily, but the structural elements that localize individual ore shoots may be so small or so obscure as to escape recognition until the ore itself is exposed.

Numerous minerals contain quicksilver but, in this country, most of the metal comes from cinnabar. The principal deposits are conspicuously deficient in other metals and many are remote from deposits of other metals, or even from other large quicksilver lodes, although quicksilver in small amounts occurs in several other kinds of deposits. It seems that quicksilver ore shoots form only after the salts of other metals have been separated, either by prior deposition or otherwise, and that the more valuable form only under special conditions, now only partially understood. Some gangue minerals, especially at early stages, formed by replacement, but the cinnabar crystallized mainly in open spaces. In many places the rising solutions mingled with ground water, which helped to localize lodes and districts.

## *GOLD MINERALIZATION IN MINOR IGNEOUS INTRUSIONS.*

W. W. MOORHOUSE.

(Introduced by E. S. Moore)

The association of gold mineralization with or in porphyry dikes and bodies is known in many parts of the Canadian shield. This relationship has frequently been considered to be purely structural or genetic only in

the sense of derivation from the same magmatic source. Evidence of a much more intimate connection is given from an occurrence of auriferous pyrite as disseminations and in quartz-carbonate veins in albitite porphyry in Bryce township, Ontario. The porphyry is in part a normal dike, in part a replacement of associated schists. Stringers extending into the schists are enclosed by a zone of albitization which resembles the porphyry itself. This, with other examples from the same area, is believed to indicate that replacement and intrusion by albitic material were accompanied by the gold-pyrite mineralization. Comparisons are given with other gold deposits associated with porphyry and albitite dikes and bodies in Canada.

Auriferous quartz-sulphide mineralization which has been discovered in small altered dioritic bodies in relationships of the veins to these intrusives suggests a rather close genetic connection. Reference is made to comparable gold deposits described in the literature.

## *GEOLOGY OF THE NICKEL SILICATE DEPOSIT NEAR RIDDLE, OREGON.*[1]

WILLIAM T. PECORA AND S. WARREN HOBBS.

(Introduced by W. D. Johnston, Jr.)

On Nickel (Piney) Mountain, 5 miles northwest of Riddle, Douglas County, Oregon, an irregularly distributed surficial blanket of weathered rock contains discontinuous boxwork veinlets of quartz and garnierite, a hydrous magnesium-nickel silicate. The deposits richest in nickel are underlain by unserpentinized peridotite and are located with one exception on terraces or gentle slopes between the summit of the mountain (3,535 feet) and a conspicuous terrace (2,000 feet). The weathered blanket has a top brick-red soil layer a few feet thick, an underlying limonitic layer containing boxwork veins, and deep roots of weathered rock in unweathered rock. The quartz-garnierite boxwork veins fill fractures in weathered and unweathered rock.

The ore mineral is pale yellow to dark green, brittle and unctuous when dry, pasty when wet, and contains 2 to 36 per cent of nickel. Chemical analyses, optical studies, and X-ray photographs indicate that garnierite is a nickel-rich deweylite. Garnierite has a deeper color shade, higher refractive index, and less magnesium than deweylite, and is intimately associated with quartz in the same vein. Deweylite is colorless to greenish yellow and is commonly free of quartz.

The nickel and magnesium are believed to have been derived essentially from weathering of olivine in the unserpentinized peridotite under climatic conditions existing in the geologic past, presumably before the dissection of the pre-Pleistocene 2,000 feet terrace. Under present climatic conditions the deweylite (nickel-poor garnierite) is chemically attacked by surface waters, causing nickel enrichment of deweylite in place to form garnierite, precipitation of $SiO_2$ to form quartz, and supergene deposition of garnierite itself in open fractures.

## FOUNDATION AND SLOPE PROBLEMS AT YOUGHIOGHENY DAM.

SHAILER S. PHILBRICK AND ROBERT H. NESBITT.

The Pittsburgh Office of the United States Engineer Department is constructing a large earth dam across the Youghiogheny River, one mile south of Confluence, Pa. Excavation in connection with the dam and appurtenances has uncovered the Conemaugh Formation from the Mahoning clays to the top of the Morgantown sandstone, a vertical section of approximately 470 feet.

The design called for a structure 180 feet high. The occurrence of weak shales and fire clays, below the stream and in fifty per cent of the abutments, were the determining factors in the construction of an earth dam with a side hill spillway instead of a concrete gravity dam. The construction of the spillway involves a cut approximately 300 feet high through the weathered sandstones and unstable clays of the upper-middle Conemaugh. All of the horizons to be exposed in excavation were thoroughly explored by core drilling and physical tests. These studies were supplemented by detailed analysis of slope conditions in some of the largest cuts through the Conemaugh in Western Pennsylvania.

Geological investigations for the dam have furnished a detailed section of the middle Conemaugh group which should prove valuable in correlating the same horizons in Maryland and West Virginia.

## MOVEMENT OF MINERALIZING SOLUTIONS IN THE PICHER DISTRICT, OKLAHOMA-KANSAS.

RICHARD E. STOIBER.

(Introduced by W. H. Newhouse)

The direction of flow of the mineralizing solutions was studied at many localities in the mines of the Picher lead-zinc district in Oklahoma and Kansas. Direction of flow was determined from a study of crystals deposited in open space by noting preferred growth on the stoss side of crystals, overgrowths of later crystals on the stoss side of earlier ones and crystal deposition on the stoss side of irregularities in cavity floor or roof. The horizontal components of the flow directions indicate movement of the solutions away from the Miami Shear Trough, approximately NE and NW to the NW of the trough and SE and SW to the SE of the trough, with little local variation. These directions are believed to indicate the pattern of the fractures along which solutions traveled in this area. Ore runs appear to have formed when the solutions reached the structures favorable for ore deposition described previously by other investigators.

## ORIGIN OF SULPHIDES IN THE NICKEL DEPOSITS OF MOUNT PROSPECT, CONNECTICUT.

EUGENE N. CAMERON.

Nickel-bearing deposits occur at a number of places in the intrusive complex of Mount Prospect, near Litchfield, Connecticut. The ores are noritic and pyroxenitic rocks containing varying amounts of pyrite, pyr-

rhotite, pentlandite, and chalcopyrite. The rocks are largely free from characteristic hydrothermal alteration products. This feature and the textural relations of sulphides to silicates in the ores have previously been taken to indicate that the sulphides are of magmatic or late magmatic origin.

A detailed study of the intrusive complex has furnished field data and new microscopic evidence which relate to the problem of sulphide origin. Mapping has shown that the principal ore-bearing rocks comprise intrusives of three different types: mafic norite, norite, and hypersthene pyroxenite, intruded in the order named. The nickel deposits are concentrations of sulphides at or near the margins of these intrusives. Apart from the sulphides, the rocks consist essentially of hypersthene, clinopyroxene, plagioclase, hornblende, and biotite. Indications have been found that hornblende, at least in part, and biotite developed after solidification of the rocks. The sulphides appear to have been introduced later and to have formed chiefly by fracture-filling and by replacement of the various silicates. No specific conclusions have been reached as to time of sulphide deposition for the deposits as a group, but the presence of introduced sulphides in fine-grained dikes cutting mafic norite and norite at two deposits suggests that a considerable interval elapsed between solidification of the latter rocks and development of sulphides.

## *AUTORADIOGRAPHY OF ORES.*

CLARK GOODMAN AND GEORGE A. THOMPSON.

Using stray slow neutrons from the M. I. T. cyclotron on elements having large nuclear cross-sections for $(n, \gamma)$ reactions and yielding radioactive isotopes of convenient half-periods, autoradiographic studies of a number of ores have been made. The locus and relative concentrations of these elements in the constituent minerals is determined by placing polished sections of the activated ores in direct contact with photographic film. The source of the effective B-radiation is ascertained from the decay rate and intensity of the activity. Manganese, gold, cadmium and phosphorus bearing ores have been studied by this method. Further investigations are in progress with the purpose of extending the method to other elements, of making the method quantitative, and of applying the method to thin sections.

## *SETTLING OF HEAVY MINERALS IN A GRANODIORITE DIKE AT BRADFORD, RHODE ISLAND.*

ALONZO QUINN.

A granodiorite dike at Bradford, Rhode Island, has a thickness of sixty-five feet, an east-west strike, and a dip of 28 degrees south. Heavy mineral separation of samples from different parts of the dike indicate that the proportion of heavy minerals increases systematically toward the base of the dike. This is shown also by thin-section studies of specimens from different parts of the dike and by studies of a dark zone at the base of the dike.

The systematic increase of heavy minerals toward the base seems to be due to crystal settling for several reasons. (1) The minerals which are

concentrated toward the base crystallized early in the solidification of the rock. (2) These minerals were considerably heavier than the granodiorite magma. (3) They are distributed through the body of the rock and are not concentrated along permeable zones as they would be if deposited by later hydrothermal solutions. (4) The heavy minerals are especially concentrated in a dark zone along the base and appear to fill depressions in the slightly irregular floor.

The settling appears to have occurred when the magma was moving upward along the dike, as is indicated by the fact that the zones of equal proportions of heavy minerals are almost parallel to the base instead of horizontal. The small size of the settled grains, with zircon crystals as small as 0.10 millimeters by 0.03 millimeters, indicates a low viscosity of the magma.

## *RADIOACTIVE AUREOLES AROUND SOME ORE DEPOSITS.*

NORMAN B. KEEVIL.

Mineral deposits are sometimes less, sometimes more radioactive than country rock. When the ore body is relatively high in activity, concentrations of radioactive material in the vicinity of the deposit have been observed in some instances. At Gilman, Colorado, where a series of samples collected during a Lundberg geophysical survey was examined, the activity was observed to be higher near radioactive ore and to decrease in concentration away from the ore body. Some of the activity appeared to be due to diffused radon, but spectrochemical concentrations of silver, copper, lead, and zinc associated with the radioactivity suggested that much of the radioactive material was introduced during mineralization. The results suggest that sample analysis may be useful in indicating proximity to ore in some instances.

## *CORRELATION OF THE BUNKER HILL AND SULLIVAN FRACTURE PATTERN WITH REGIONAL STRESSES.*

ROGER H. MCCONNEL.

(Introduced by H. E. McKinstry)

The large horizontal component of movement to the right on the Osburn Fault, the major tectonic feature of the Coeur d'Alene district, Idaho, suggests that the maximum normal stress producing this fault was oriented in a northwesterly and steeply-dipping direction.

It is suggested that the northwesterly strike and steep dip of the majority of Coeur d'Alene district veins is a reflection of the regional stress direction which produced the Osburn Fault. In other words, that the prevailing attitude of the majority of veins represents the direction of maximum normal stress affecting the region.

In various areas of the district, there are numerous details of the fracture pattern which are apparently anomalous. On closer study, many of these appear to result from local re-orientation of the regional stresses within blocks bounded by fractures subsidiary to the Osburn Fault.

Some of these apparently anomalous details are well illustrated by the complicated Bunker Hill and Sullivan fracture pattern. Evidence is presented suggesting that the development of the Bunker Hill fracture pattern

was initiated by the regional stress, and was progressively modified by re-orientation of the local components affecting each successively produced block of ground.

The bulk of Bunker Hill and Sullivan ore has come from the ore bodies in which the component bands of ore lie in the directions of maximum normal stress within the complex fracture pattern. The remainder has come from those sections of shears favorably oriented for reopening by the regional stresses or their modified components.

## *ORIGIN OF THE QUARTZ DEPOSIT AT FAZENDA PACU, BRAZIL.*

PAUL F. KERR AND ALBERTO ERICHSEN.

The deposits of crystal quartz now being worked at Fazenda Pacu, Minas Geraes, Brazil, provide the most important source of commercial crystals in Brazil. Crystals occur in a deeply weathered zone along the contact between the Archean and overlying Silurian sediments. Decomposition of the matrix obscures direct evidence of origin, but the quartz is believed to have been formed originally by coarse crystallization in veins. In addition to deposits formed in situ, clay and gravel deposits occur in which the gravels are rounded quartz crystals.

## *SOLUBILITY OF SOLIDS IN "GASES" OR "VAPORS."*

GEORGE W. MOREY AND EARL INGERSON.

The transport in significant quantity of solid material by means of a gas or vapor at high temperature and pressure is dependent on solubility of the solid in the vapor. By this is meant that in unit volume of the vapor the content of solid is greater than corresponds to its own vapor pressure at the temperature and total pressure under consideration. In our work we have found transport and deposition of corundum, rutile, sillimanite, quartz, and amorphous silica by water at temperatures from 500 to 1000°, and at pressures from 3000 to 15,000 pounds. These experiments and products will be described.

The consideration of problems of solubility of solids in vapor requires rigid definition of the terms "gas," "vapor," and "fluid" as applied to phases coexisting in several-component systems under conditions in which definitions which are logical and complete for a one-component system no longer are applicable. Definitions of "gas" and "vapor" are proposed.

The further discussion of the problem of the solubility of non-volatile solids in a vapor will be made with the aid of diagrams illustrating the variation of temperature, pressure, and composition in binary systems in which different types of critical end-points are assumed.

## *CHROMITE DEPOSITS OF THE PHILIPPINE ISLANDS.*

DEAN F. FRASCHE.

The chromite deposits of the Philippines occur in isolated masses of ultrabasic rocks which are in general found along the eastern and western borders of the Island group. The ultra-basic rocks are highly serpen-

tinized and are difficult to distinguish in the field but petrographic studies reveal them to be composed essentially of three intergrading rock types, dunite, saxonite and pyroxenite. Of these three types, saxonite occurs in greater volume than either dunite or pyroxenite. Varying amounts of chromite are found in the different rocks but the known commercially important deposits appear to be confined entirely to the serpentinized dunite. Locally in the Zambales area, gabbro and diorite intrude the chromite deposits, but these less basic rocks appear to be confined to the refractory grade ore bodies. The chromite is considered to be genetically related to the dunite and is probably of early magmatic origin.

Although chromite occurs in commercial quantities on several of the Islands, the largest deposits are found in Zambales Province, Luzon. The individual deposits vary greatly in size, ranging from a few hundred to more than ten million metric tons. The grades of chromite now being produced in the Zambales area are classified according to their industrial uses, namely, metallurgical ores, chemical ores and refractory ores.

Philippine reserves of chromite of all grades are estimated to be 10,890,500 metric tons. Of this total 10,120,000 metric tons are refractory grade, 450,500 tons are chemical grade, and 320,000 tons are metallurgical or submetallurgical grade.

## *THE RELATION OF GEOLOGY AND PHYSIOGRAPHIC HISTORY TO WATER SUPPLY, FLOODS, AND SOIL EROSION IN THE MUSKINGUM WATERSHED, OHIO.*

H. ANDREW IRELAND.

The glaciated and unglaciated portions of the Muskingum watershed have distinct contrasts in soil, topography, drainage patterns, and subsurface conditions. Deeply-entrenched valleys, filled with outwash material, have great porosity, rapid percolation, and serve as reservoirs for sub-surface water from which stream flow is maintained. Similarly entrenched valleys, not connected with the ice front, filled with silt and clay eroded from the unglaciated basins, have a high water table, slow percolation, low gradients, and do not allow sustained stream flow. The large percentage of run-off from the steep slopes and thin soils in the unglaciated area causes much soil erosion. Run-off reaches the valleys quickly, but the flow is retarded on the broad valley bottoms, which have low gradients. Flood volumes, therefore, have low crests and extend over several days. The valley meanders of the major streams in the unglaciated area, inherited from pre-glacial drainage systems have the effect of retarding flood flows. Glaciated areas have gentle slopes, deeper soil profiles, and less soil erosion. The alteration of drainage systems by the glaciers causes a staggering of the time when flood crests from many of the tributary valleys enter the main valleys. One result is a reduction of flood crests on the main streams. Depletion curves, ground-water measurements, and ground-water-storage curves are evidence of differential absorption. Similarly, unit graphs are used for discussion of surface run-off. Major differences are explained on the basis of geologic and physiographic history.

## MINERALIZATION OF THE AJO COPPER DISTRICT, ARIZONA.

JAMES GILLULY.

The New Cornelia orebody at Ajo is a deposit of chalcopyrite with subordinate bornite and other minerals disseminated in a mass of quartz monzonite porphyry of early Tertiary (?) age. Petrographic study shows that the orebody lies in part of the porphyry with a peculiar groundmass texture that is believed to date from a time prior to consolidation. Pegmatites of probable replacement origin were formed later, and the monzonite surrounding them was heavily impregnated with finer-textured potash feldspar and quartz. Sulphide impregnation, which followed, is heaviest in and near the pegmatites, and fades out into a zone of sericitization peripheral to the zone of feldspar impregnation. The mineralization is believed to have been by an unbroken continuation of magmatic evolution into a hydrothermal stage. No discontinuities are recognized in the sequence of alterations that linked the magmatic stage with that of sulphide mineralization, although specular hematite, which is very abundant, seems clearly governed by different controls, and may record a discontinuous—pneumatolytic—stage. It is uncertain, but appears probable that sulphide mineralization and hydrothermal alteration reverted to their former controls after the period of specularite formation.

Weathering of the deposit has taken place in two stages: an earlier, during which there was notable downward enrichment, and a later, during which the copper was oxidized essentially in place. Between the two periods, the block containing the deposit was tilted about 60°. No satisfactory explanation of the different behavior during the two erosion cycles has been discovered.

## NOTES ON THE ORIGIN OF THE MANSFELD COPPER DEPOSITS.

CHARLES HENRY WHITE.

A brief outline of the structure of the region is followed by observations of conditions underground at the Wolf shaft at Eisleben in June 1932, which indicate that the deposits are epigenetic.

## ARTIFICIAL RECHARGE OF GROUND WATER.

DAVID G. THOMPSON.

Artificial recharge of ground water has been carried on successfully for many years, notably in California, by spreading water from surface streams over the ground. Attempts to recharge by means of wells or shafts have met with different degrees of success. In some areas of cavernous limestone, notably in Florida, large quantities of water have been put into wells. In contrast, no examples are known where surface water has been succesfully put into wells penetrating porous granular materials for any considerable period without filtration. On Long Island and elsewhere much water has been pumped from wells for air-conditioning, and returned to the ground through a closed system; but, in some instances, there has been a noticeable rise of the temperature of the ground

water; and some wells, perhaps due to poor construction, have become clogged. In one place cold water, recharged through wells in winter, has been pumped out in summer at a not much higher temperature.

The opportunity for recharge—whether by water spreading or through wells or shafts—differs depending upon whether water table or artesian conditions exist. Obviously, recharge of an artesian aquifer can be accomplished by water spreading only in its area of outcrop, but this may be too far from areas of heavy pumping to be very effective. In contrast, although recharge by wells may be carried on anywhere, it will be most effective in the areas of heavy pumpage where there has been considerable decline in the water table or piezometric surface.

The paper discusses certain factors to be considered when undertaking recharge by means of wells.

## *THE EFFECT OF ELECTROLYTES ON THE SOLUBILITY OF METAL SULPHIDES IN VEIN SOLUTIONS.*

ROBERT M. GARRELS.

The determination of metal sulphide solubilities in mixed electrolytes has received very little attention from geologists because of the analytical difficulties inherent in the determination of the extremely small amounts of sulphides present in vein solutions.

This difficulty is overcome by an indirect method, based upon measurements of the EMF of appropriate galvanic cells containing mixed electrolytes approximating the composition of vein solutions.

The following generalizations can be made from experimental work:

1. Addition of electrolytes to metal sulphide solutions may increase or decrease the solubility of the sulphide many thousands of times.
2. Small amounts of electrolytes (up to 0.1 molal) increase the solubility of metal sulphides.
3. The effect of larger amounts of electrolytes is generally unpredictable on theoretical grounds, and may either cause a further increase in solubility or a rapid decrease, depending upon the specific mixture chosen.

## *EMERGENCY RESERVES OF MANGANESE ON THE CUYUNA RANGE, MINNESOTA.*

FRANK F. GROUT.

The files of the Minnesota Geological Survey, though incomplete, now show in the north part of the Cuyuna Range about 10 million tons of high silica manganiferous oxide, largely of "black ore" type, but too high in silica to be merchantable in ordinary times.

Several drilling campaigns of recent years are not yet available to the Survey but would add to this; and there remain a number of promising properties that have never been explored. It is probable that these would increase the estimate of such material to perhaps 3 to 5 times as many tons.

Under the best manganiferous oxide ores at many places are fresh "green carbonate slates" which carry from 1 to 15 per cent manganese. This is the original underlying manganiferous formation and constitutes a reserve that is known to be enormous, but which is not yet adequately explored.

# SCIENTIFIC NOTES AND NEWS

KENNETH K. LANDES, recently chairman of the department of geology at the University of Kansas and geologist for the state of Kansas, is the new chairman of the geology department at the University of Michigan. E. S. BASTIN of the University of Chicago recently spoke before the department on "Some Problems of Ore Deposition."

The INSTITUTION OF MINING AND METALLURGY OF LONDON has moved temporarily to the Royal School of Mines, London, S. W. 7

IRA JORALEMON has recently returned from examination of a zinc-lead property in southeastern Alaska.

WILLIAM BURNS is chairman of the Mineral Resources Committee of the State Defense Council of Connecticut which is investigating state resources that may be used for defense or emergency purposes, or to save long transport. Others of the committee include ALAN M. BATEMAN, J. B. LUCKE, JOSEPH PEOPLES, E. L. TROXELL, C. R. HOOVER, WILLIAM AGAR and B. B. GOTTSBERGER.

H. F. BAIN returned to the Philippines in October and will not be back in the states until spring.

E. Y. DOUGHERTY is now with the U. S. Bureau of Mines in Tucson, Arizona.

A. W. BRUNE of the Nevada Consolidated Copper Corp. has joined the U. S. Geological Survey at Sacramento, California.

F. C. KRUGER is assistant geologist for the Cerro de Pasco Copper Corp., Cerro de Pasco, Peru.

J. O. FULLER, formerly assistant professor of geology at Mount Union College, is now instructor in geology at Ohio State University.

W. P. Goss, mine superintendant of O'Okiep Copper Co. Ltd., is planning to return soon to the United States.

LIVINGSTON WERNECKE, vice-president and general manager of the Treadwell Yukon Corp., was killed in October when his private plane crashed off the coast of British Columbia.

W. B. TIMM became Director of the Mines and Geology Branch of the Canadian Federal Department of Mines on the first of November.

W. A. NELSON, on leave of absence from the University of Virginia, has been appointed priority coordinator of mines under the OPM. M. M. LEIGHTON has become a member of the Advisory committee on Metals and Minerals of OPM.

R. H. KING has joined the U. S. Geological Survey to work on potash at Carlsbad, New Mexico.

RAMON ROSAS has been made chief of the exploration department of Cia. Huanchaco de Bolivia, Pulacayo, Bolivia.

D. F. CAMPBELL has returned from three years as geologist for Cia. Minera de Oruro, Bolivia, and is at present at the University of Arizona.

L. B. MATHER, JR., who has been with the Field Museum of National History in Chicago, is junior geologist with the central concrete laboratory of the U. S. Military Academy at West Point.

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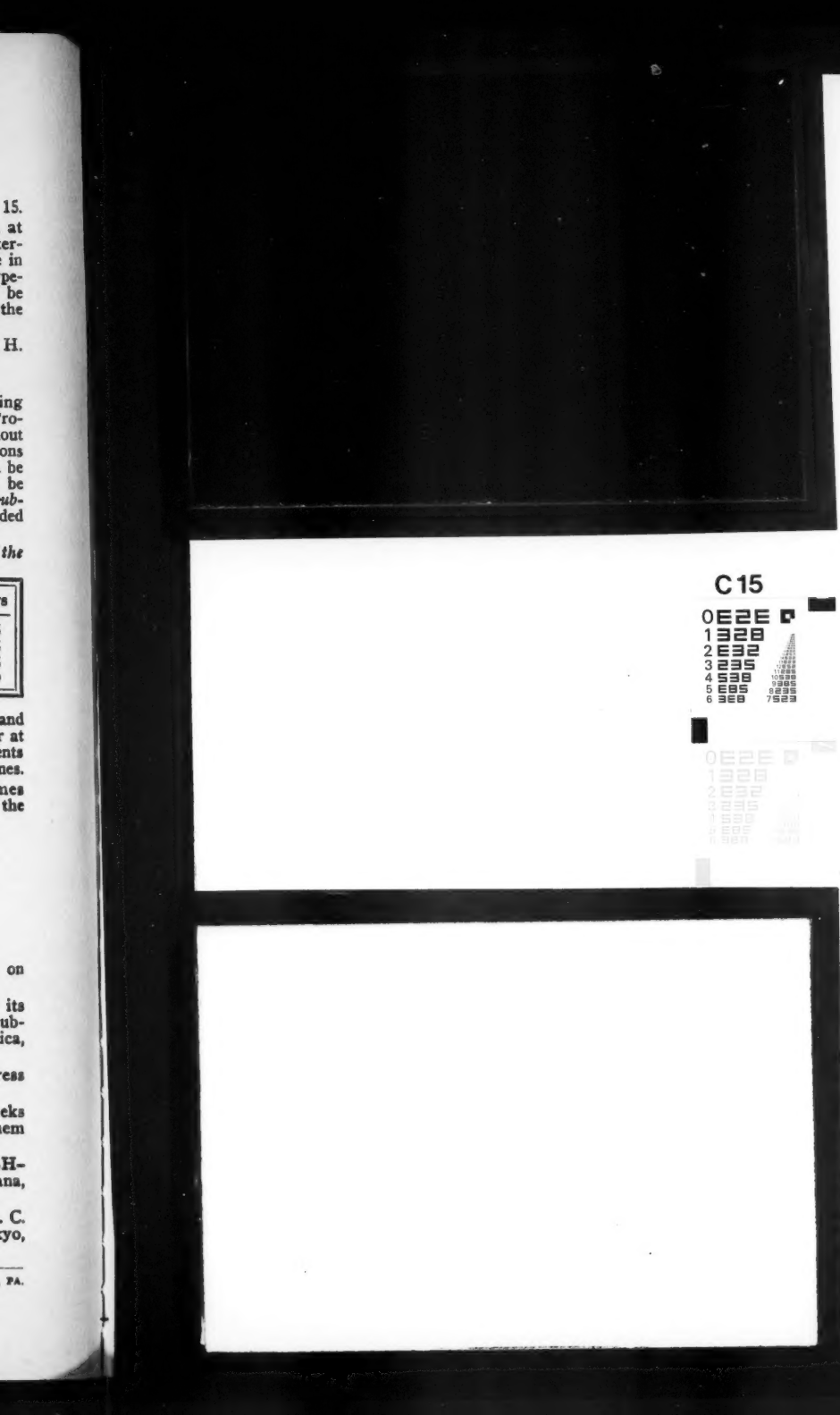
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